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Effects of Visual, Auditory, and Tactile Navigation Cues on Navigation Performance, Situation Awareness, and Mental Workload

by Bradley M. Davis

ARL-TR-4022 **February 2007**

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ARL-TR-4022 **February 2007**

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
February 2007	Final	

4. TITLE AND SUBTITLE	
Effects of Visual, Auditory, and Tactile Waypoint Location Cues on Navigation Performance, Situation Awareness, and Mental Workload	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER** 62716AH70
Bradley M. Davis (ARL)	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory Human Research & Engineering Directorate Aberdeen Proving Ground, MD 21005-5425	**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-TR-4022
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBERS

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Two experiments were conducted to assess the effects of navigation display modality on navigation performance, situation awareness, mental workload, and modality preference. Directional cues to a series of waypoints were provided visually, aurally, and tactilely in the within-subjects design. Each experiment was performed in a virtual environment by U.S. Army Soldiers, 14 in the first experiment, 18 in the second experiment. Results from both experiments indicate that augmented visual displays reduced time to complete navigation, maintained situation awareness, and drastically reduced mental workload in comparison to the other display modalities.

15. SUBJECT TERMS

mental workload; navigation; situation awareness; tactile

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Bradley M. Davis
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** (*Include area code*)
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	65	573-329-8704

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction

This study is one of several investigations in an iterative cycle of modeling and experimentation to achieve the objective of the Situational Understanding as an Enabler for Unit of Action Maneuver Team Soldiers Army Technology Objective (ATO). The objective of the ATO was to develop, demonstrate, and transition unit of action Soldier information systems that address differences in the way Soldiers gain situational understanding and enable planning and acting within the adversary's decision cycle.

To help meet the objective of the ATO, Mitchell, Samms, Glumm, Krausman, Brelsford, & Garrett (2004) built Improved Performance Research Integration Tool (IMPRINT) models to simulate tasks of each of the crew positions of Future Combat Systems' manned ground vehicle (MGV) variants. The MGV variants modeled were the Mounted Combat System (MCS), infantry carrier vehicle (ICV), non-line of sight cannon (NLOS-C), non-line of sight mortar (NLOS-M), and the reconnaissance and surveillance vehicle (RSV). These IMPRINT analyses have identified areas of operator overload. Across all the MGV variants, the driver was often the crew member with the most instances of operator overload as a result of the demands of the tasks associated with driving (manipulations, awareness, and visualizations) (Mitchell et al., 2004). These driving tasks have been validated against other driving models and have been determined to represent adequately the driving function (Wojciechowski, 2004).

Recommendations of ways to mitigate operator overload were suggested by Mitchell et al. (2004). The recommendations included using tactile or auditory displays with the driver's integrated display to reduce the use of visual and cognitive resources of the driver. In addition, spatial audio was recommended as a means of assisting navigation.

These recommendations stem from multiple resource theory (MRT) (Wickens & Hollands, 2000), which was also the basis for the IMPRINT workload analysis. Multiple resource theory proposes that people have several independent capacities with resource properties and that some resources can easily be used simultaneously while other combinations are much more difficult. Therefore, tasks using compatible resources can usually be performed together, while competition for the same modality can produce interference. The degree of task compatibility or interference affects the level of performance.

This study focused on the driver's task of navigation. Navigation is a process performed by the driver, which includes all the driving tasks: manipulation, awareness, and visualization. These tasks are primarily visually and cognitively oriented. A fundamental element of navigation is having the knowledge of one's current location and the location of the destination, which may be presented to the driver in a variety of ways.

From the recommendations by Mitchell et al. (2004), which are supported by MRT, several display modalities for presenting navigation waypoint information were designed, including visual, monaural and spatial audio, and tactile displays. A comparison of these displays and a baseline display in terms of navigation performance, situation awareness (SA), and mental workload was conducted. It was hypothesized that the alternate display modalities would provide greater navigation performance, increased SA, and decreased mental workload than the baseline display configuration because of the improved information processing provided by the displays. It was not hypothesized which specific waypoint display modality would provide best performance, SA, or mental workload but that there would be significant differences among the different experimental conditions for each dependent variable.

2. Objective

The objective of this study was to assess the effects of waypoint display modality on navigation performance, SA, mental workload, and modality preference. To reach this objective, two experiments were conducted: the first laid the groundwork for the study and the second refined the methods and validated the results of the first experiment.

3. Experiment 1

3.1 Method

3.1.1 Participants

The participants for the first experiment were 14 male U.S. Army Soldiers, ranging in age from 20 to 27 years (mean [*M*] = 22.0 years, standard deviation [*SD*] = 2.25 years). Participants had from 0.7 to 3.6 years of military service (*M* = 2.21 years, *SD* = 0.7 years) and a similar amount of time in their military occupational specialty (MOS). All participants were armor crewmen, MOS 19K, or cavalry scout, MOS 19D and were qualified as drivers of the M1 Abrams tank. All the participants had normal visual acuity and color vision in both eyes. Although participants were not given a hearing threshold level test, all participants reported no suspected hearing loss or damage. The voluntary, fully informed consent of the persons used in this research was obtained as required by 32 Code of Federal Regulations (CFR) 219 and Army Regulation (AR) 70-25. The investigator has adhered to the policies for the protection of human subjects as prescribed in AR 70-25 (HQDA, 1990).

3.1.2 Apparatus

The participants sat at a computer workstation with two personal computers (PCs), each equipped with a 3.0-GHz Intel Pentium 4 central processing unit, ATI[1] Radeon[2] 9800 Pro 256 MB graphics adapter, and 1 GB of random access memory (RAM). A ViewSonic VG900b 19-inch liquid crystal display (LCD) monitor set at 1024 x 768 resolution was connected to each PC as a primary display and navigation display. The primary display was placed at a comfortable distance, directly in front of the participant. The navigation display was placed immediately to the right of the primary display and angled toward the participant. The navigation display was only used for two of the experimental conditions and was turned off for all other experimental conditions. A Cyber Acoustics AC-200 supra-aural stereo headset was connected to the PC via the Creative Labs Sound Blaster Audigy[3] sound card. The input devices used for navigation were a Microsoft optical wheel mouse and Microsoft multimedia keyboard. An additional Microsoft optical wheel mouse served as the input device for the navigation display for the two experimental conditions requiring the navigation display and was moved out of the way for all other experimental conditions. Figure 1 graphically illustrates the computer workstation configuration.

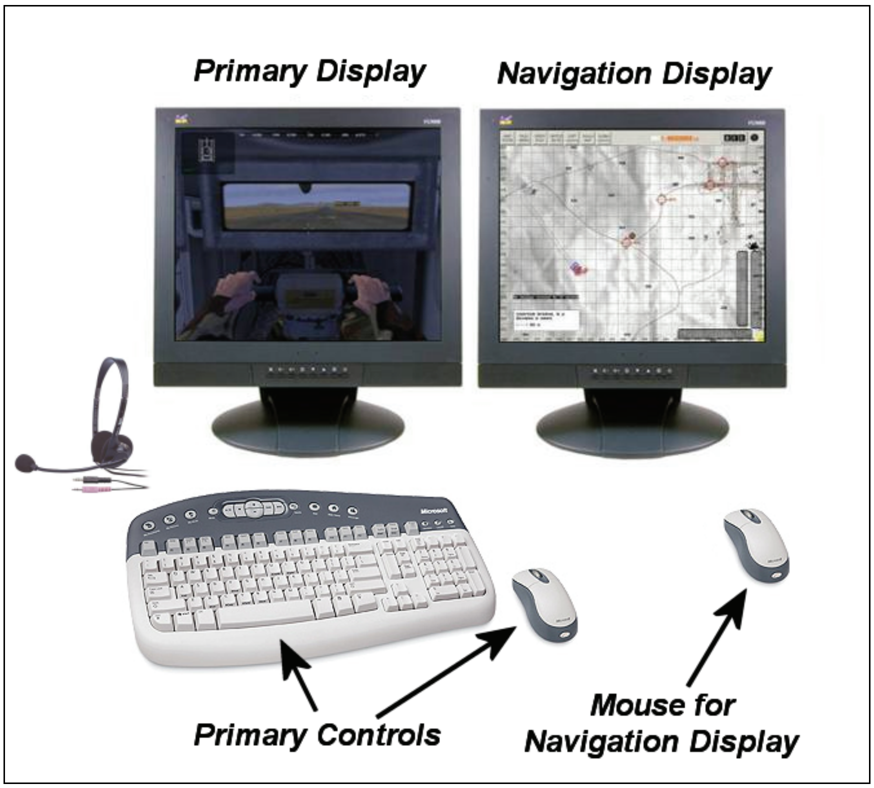

Figure 1. Apparatus configuration.

[1]ATI is not an acronym.
[2]Radeon is a registered trademark of ATI Technologies, Inc.
[3]Blaster and Audigy are registered trademarks of Creative Technology Ltd.

VBS1[4] was used as the virtual environment for these experiments. VBS1 is a military training and simulation system used by the U.S. Marine Corps and the U.S. Army National Guard. VBS1 is an immersive three-dimensional first-person shooter-style simulation, with the additional ability to command and control many vehicles and aircraft. The simulation allows for cooperative or competitive multi-player scenarios. Navigation scenarios were created with the VBS1 scenario editor which allows for complex scenario editing, custom scripting, and a means for external file input and output, allowing simple integration of the tactile equipment used.

3.1.3 Task

Each navigation scenario consisted of a series of three waypoints. Each waypoint included a visible object, such as an abandoned tank (see figure 2), to assist the participant in identifying the waypoint and include an aspect of realism. Two of the waypoints were in open, rolling, desert terrain. Another navigation segment placed the waypoint in an urban area (see figure 3). The first navigation segment was 1 km long, and the second and third segments were 2 km each. The locations of the waypoints were randomized so that a participant would not learn and memorize the navigation route. Randomly, one of the three navigation segments included identifying and navigating around a 200-m by 1000-m minefield, marked with danger signs around the perimeter (see figure 4). Diagrams of the scenario maps are provided in appendix A.

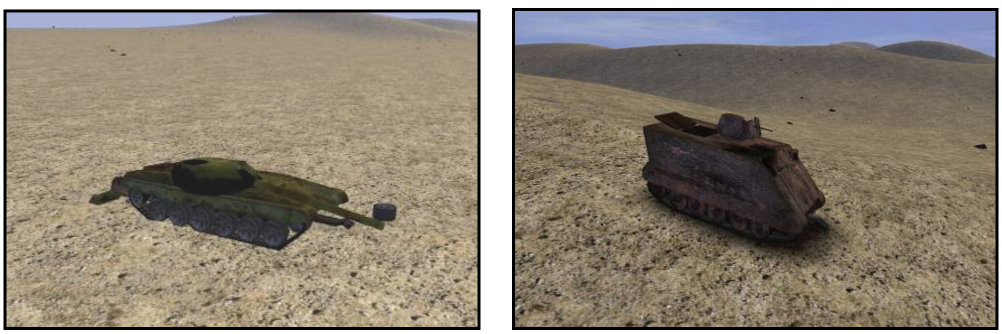

Figure 2. Visible objects at two of the waypoints in open terrain.

Figure 3. Visible object at the waypoint in urban terrain.

[4]VBS1 is a trademark of Bohemia Interactive Studio.

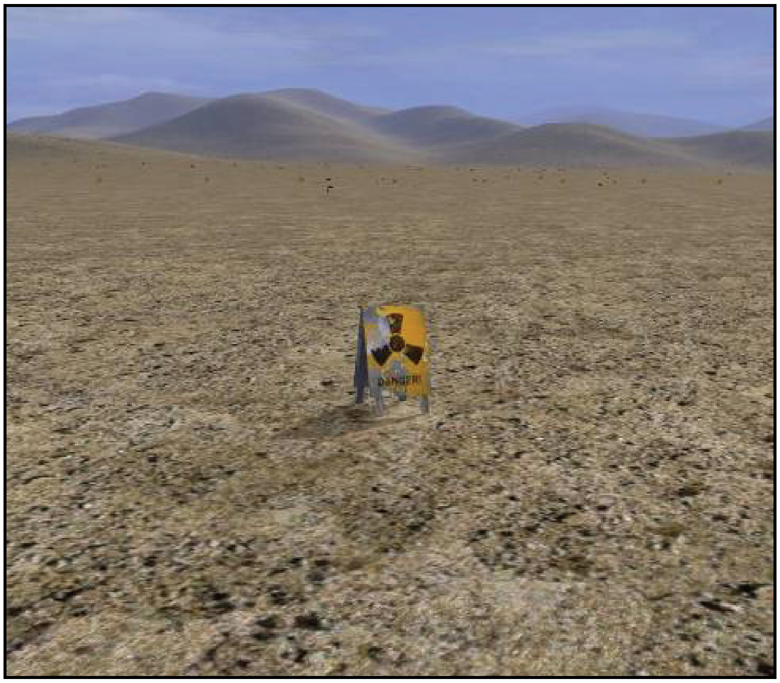

Figure 4. Minefield marker.

3.1.4 Questionnaires

Several questionnaires were used as measures of the dependent variables. Each is described in more detail next.

3.1.4.1 Situational Awareness Rating Technique (SART)

SA was measured with the SART questionnaire. The metric combines 10 generic constructs derived from knowledge elicitation techniques with air crews into three broad domains: (a) attentional demand, which includes constructs of instability of situation, variability of situation, and complexity of situation; (b) attentional supply, which includes the constructs of arousal, spare mental capacity, concentration, and division of attention; and (c) understanding, which includes the constructs of information quantity, information quality, and familiarity (Taylor, 1990). These three broad domains are combined to form an overall SART score by the formula SA = Understanding − (Demand − Supply). A high overall SART score indicates a high (better) level of SA, whereas a low SART score indicates a low (worse) level of SA. The SART questionnaire used in these experiments is shown in appendix B.

3.1.4.2 National Aeronautics and Space Administration (NASA) Task Load Index (TLX)

Mental workload was measured with a NASA-TLX questionnaire. The NASA-TLX is a psychophysical technique for mental workload measurement, which has sensitivity to different levels of task demand. The NASA-TLX provides an overall subjective workload score based on a weighted average of ratings on six subscales: mental demand, physical demand, temporal demand, own performance, effort, and frustration (Hart & Staveland, 1988). For these experiments, the physical demand subscale was removed because of the non-physical nature of the task. After each subscale is rated, the participants select from combinations of paired comparisons, the more important contributor to workload for the task performed to create a weighting for each subscale. The weighted ratings are then combined to create an overall NASA-TLX score. A high NASA-TLX score indicates a high level of mental workload, and a low NASA-TLX score indicates a low level of mental workload. The NASA-TLX questionnaire used in these experiments is included in appendix B.

3.1.4.3 Modality Preference

To assess modality preference, a modality evaluation questionnaire was designed to allow the participant to subjectively rate each experimental condition. The questionnaire consisted of seven question items using a five-point Likert type scale (1 = strongly disagree; 5 = strongly agree), except for one negatively scored question item in which the scale values were reversed. We created an overall modality rating score by combining the seven question items and averaging the ratings from each item. The modality evaluation questionnaire is included in appendix B.

3.1.5 Experimental Design

Experiment 1 was a single factor within-subjects design. The independent variable was waypoint display modality and the dependent variables were navigation performance, SA, mental workload, and modality preference. Each dependent variable and its associated measures are described in more detail following.

3.1.5.1 Navigation Performance

Two metrics were used for navigation performance: minefield navigation errors and navigation time. A minefield navigation error was recorded when a participant accidentally breached the minefield. A 30-second time penalty was assessed for breaching a minefield since doing so reduced the total distance traveled, thus decreasing the time elapsed between waypoints. Navigation time was recorded as the total time elapsed from the starting location until the participant reached the final waypoint, including any time spent planning the route and any time penalties attributable to minefield navigation errors.

3.1.5.2 Situation Awareness

The overall score from the SART questionnaire was used to measure SA.

3.1.5.3 Mental Workload

The overall score from the NASA-TLX questionnaire was used to measure mental workload.

3.1.5.4 Modality Preference

The overall score from the modality rating questionnaire was used to measure modality preference.

3.1.5.5 Seven Levels of Waypoint Display Modality

There were seven levels of the waypoint display modality independent variable: baseline, head-up icon, moving map, monaural speech, spatial speech, spatial audio tone, and tactile. Each con-dition is described in more detail following.

- **Baseline** – A static, two-dimensional (2-D) overhead map provided on the navigation display showed the starting position, waypoint locations, global positioning system (GPS) grid lines, terrain features, and landmarks but did not update or show the location or heading of the vehicle (see figure 5). The participant used the primary display along with the GPS display (in standard universal transverse mercator [UTM] format) and compass to determine his current location and heading to the next waypoint. Close views of the GPS display and compass display areas are presented in figures 6 and 7, respectively.

Figure 5. Baseline displays: primary display (left) and navigation display (right).

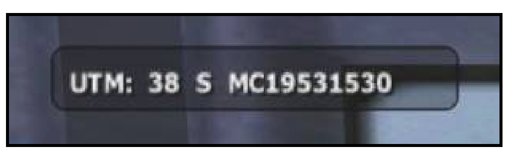

Figure 6. Close view of GPS display area of the baseline primary display.

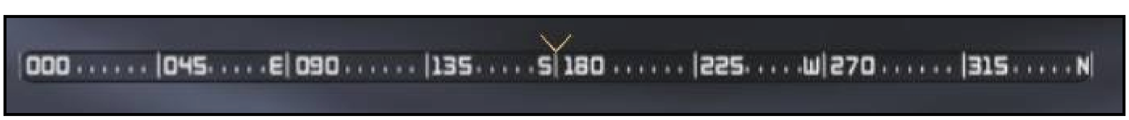

Figure 7. Close view of compass display area of the baseline primary display.

- **Head-up icon** – A yellow, square icon was overlaid on the primary display, indicating the location of the waypoint (see figure 8). When the waypoint was out of the driver's field of view (FOV), the icon changed to a triangular arrow, indicating the direction toward the waypoint. The word "waypoint" and the distance to the waypoint were shown next to the icon.

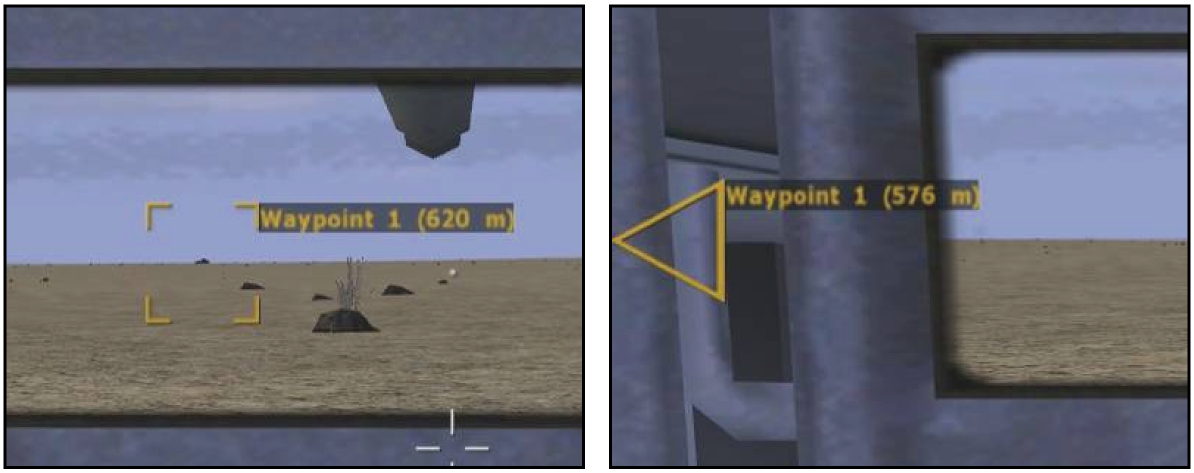

Figure 8. Head-up icon displays: close view of waypoint icon within FOV (left) and out of FOV (right).

- **Moving map** – A 2-D overhead map provided on the navigation display showed the starting position, waypoint locations, GPS coordinates, terrain features, and landmarks, exactly the same as the baseline condition but also showed the location of the vehicle updated in real time (see figure 9). The vehicle icon was at the center of the map and was rotated to show heading, while the map translated up/down/left/right to show position.

Figure 9. Moving map displays: primary display showing GPS and compass (left) and waypoint display (right).

- **Monaural speech** – Each 100 meters traveled, a synthetic speech voice (generated with the AT&T Natural Voices Text-to-Speech Engine) announced the relative direction to the next waypoint (e.g., "waypoint at 10 o'clock"). Distance to the next waypoint was communicated by the same synthetic speech voice at designated distance intervals of 1000, 500, 400, 300, 200, and 100 meters from the waypoint (e.g., "400 meters to waypoint"). The heading and distance information was presented at equal loudness to both ears.

- **Spatial speech –** Emersys Maven 3D Professional was used to create spatial audio sound representa-tions of the same synthetic speech voice used in the monaural speech condition. The software uses a generic head-related transform function to produce a stereo sound represen-tation of monaural sounds. Each 100 meters traveled, the synthetic speech voice announced the relative direction to the next waypoint, which appeared to emanate from the direction of the next waypoint (e.g., "waypoint at 1 o'clock" is heard from the 30-degree azimuth). Distance was presented in the same manner as the monaural speech condition.

- **Spatial audio tone** – Emersys Maven 3D Professional was used to create spatial audio representations of an audio tone. Each 100 meters traveled, an intermittent (600 ms on, 400 ms off) 420-Hz pure tone was presented, emanating from the direction of the next waypoint (e.g., if the next waypoint was at 2 o'clock, the audio tone emanated from the 60-degree azimuth). Tones emanating from the 4 to 8 o'clock directions were reduced in frequency by 100 Hz to reduce confusion of the mirrored tones about the 3-to-9-o'clock axis. Distance was presented in the same manner as the monaural speech modality.

- **Tactile** – The Massachusetts Institute of Technology (MIT) wireless tactile control unit (WTCU) (see figure 10) was used with 12 vibro-tactile motors positioned at the 12 clock positions in a belt worn around the participant's abdomen. Each 100 meters traveled, the WTCU provided two 1000-ms bursts with a 333-ms rest in the relative direction to the next waypoint (e.g., if the next waypoint was at 3 o'clock, the stimulus vibrated at the participant's right side). The vibro-tactile motors vibrated at approximately 70 Hz. Distance was presented in the same manner as the monaural speech modality.

The navigation display was only activated (i.e., powered on) for the baseline and moving map conditions. For all the conditions, when a waypoint was reached, the synthetic speech voice announced "waypoint reached" to make clear to the participant that he had reached the waypoint. All the generated sound files used (synthetic speech, spatial synthetic speech, and spatial audio tones) were normalized to 98% of maximum volume with Adobe Audition[5].

The author created a Greco-Latin square design by superimposing two balanced Latin squares, one for display modality and one for scenario map (see table 1). The number and letter combination in each cell of table 1 indicates the scenario that was used for each participant; display modality (1-7) is shown first and scenario map (A-G) is shown second.

[5]Adobe and Audition are registered trademarks of Adobe Systems, Inc.

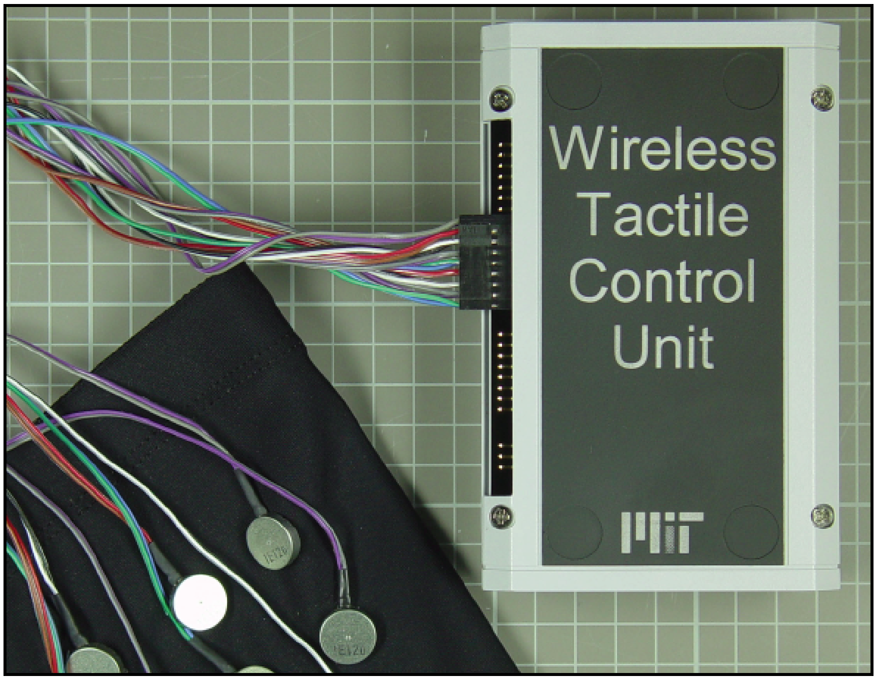

Figure 10. The MIT WTCU and vibro-tactile motors.

Table 1. Greco-Latin square design for experiment 1

		Order						
		1st	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**
Participant Number	**1, 8**	1B	2C	7A	3D	6G	4E	5F
	2, 9	2A	3B	1G	4C	7F	5D	6E
	3, 10	3G	4A	2F	5B	1E	6C	7D
	4, 11	4F	5G	3E	6A	2D	7B	1C
	5, 12	5E	6F	4D	7G	3C	1A	2B
	6, 13	6D	7E	5C	1F	4B	2G	3A
	7, 14	7C	1D	6B	2E	5A	3F	4G

3.1.6 Procedure

Volunteers received an overview of the experiment and details of the procedures and were informed of any risks involved in their participation. The volunteers read aloud and were asked to sign an informed consent form if they agreed to participate. After their fully informed, voluntary consent was obtained, participants completed a demographics questionnaire, visual acuity test, and a color deficiency test.

Each participant received 2 hours' training and practice with VBS1. First, participants were familiarized with VBS1, focusing on the controls via the keyboard and mouse. Participants then completed practice scenarios for each of the seven experimental conditions, each lasting approximately 10 minutes. Participants also received instructions and practiced completing the SART, NASA-TLX, and modality evaluation questionnaires after the final practice scenario.

After training was complete, participants completed the seven experimental conditions. Before each scenario, the participants received a short briefing reminding them of the visible markers at the waypoints, were told to be aware of and navigate around the minefield, and were told to reach each of the waypoints as quickly as possible. After completing each experimental condition, the participant completed the SART, NASA-TLX, and modality evaluation questionnaires.

3.2 Results

SPSS[6] for Windows[7], Release 13, was used for statistical analysis. Each dependent variable was analyzed for significant differences between waypoint display modalities via a repeated measures analysis of variance (ANOVA). Additionally, separate repeated measures ANOVAs were conducted with presentation order and scenario map as the independent variable. When significant differences were present ($\alpha < .05$), *post hoc* tests were performed with the least significant difference (LSD) method. There were significant effects of waypoint display modality and a significant effect of scenario map but no significant effects of order on any of the dependent variables. A summary of the repeated measures ANOVA results for modality and scenario map is presented in tables 2 and 3, respectively.

Table 2. Repeated measures ANOVA summary, waypoint display modality as independent variable.

Dependent Variable	F (6, 78)	Significance
Minefield Navigation Error	1.099	$p = .371$
Navigation Time	6.175	$p < .001$
Situation Awareness (SART)	5.496	$p < .001$
Mental Workload (NASA-TLX)	7.445	$p < .001$
Modality Preference	14.603	$p < .001$

Table 3. Repeated measures ANOVA summary, scenario map as independent variable.

Dependent Variable	F (6, 78)	Significance
Minefield Navigation Error	2.241	$p = .049$
Navigation Time	0.971	$p = .450$
Situation Awareness (SART)	0.403	$p = .875$
Mental Workload (NASA-TLX)	0.826	$p = .553$
Modality Preference	0.882	$p = .513$

3.2.1 Navigation Performance

Two metrics were used for navigation performance: minefield navigation errors and navigation time. The percentage of minefield navigation errors versus waypoint display modality is shown in figure 11. From the repeated measures ANOVA, no significant differences between waypoint display modalities for minefield navigation error were identified.

[6]SPSS, which stands for Statistical Package for the Social Sciences, is a registered trademark of SPSS, Inc.
[7]Windows is a registered trademark of Microsoft Corporation.

Significant differences were identified between scenario maps for minefield navigation errors, F (6, 78) = 2.241, p = .049. Figure 12 presents the percentage of minefield navigation errors versus scenario map. *Post hoc* analysis indicated that minefield navigation errors were greater for scenario map F than for scenario maps A and B (all $p < .05$). Similarly, minefield navigation errors were greater for scenario map E than for scenario map B ($p < .05$). Significant differences did not exist among scenario map A, B, C, D, or G (all $p > .05$).

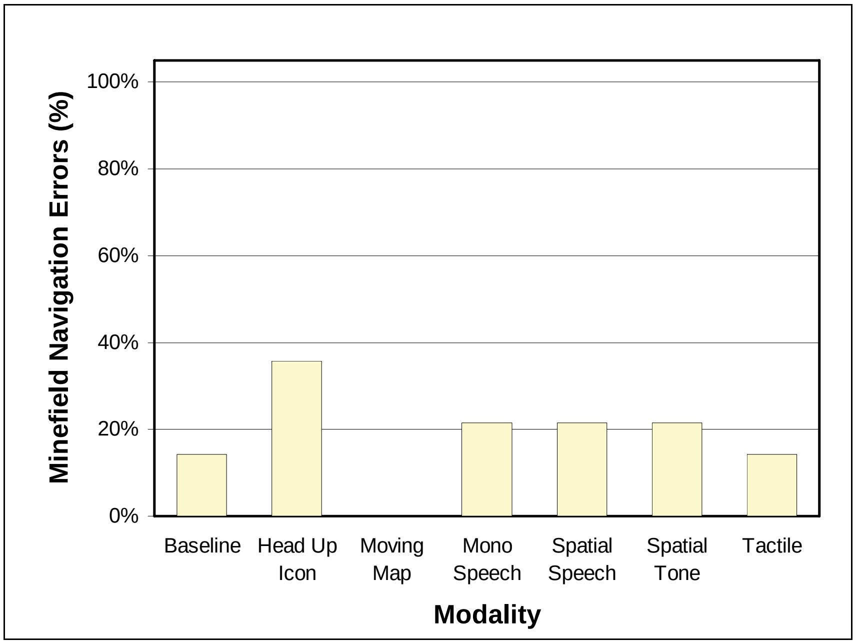

Figure 11. Minefield navigation errors versus waypoint display modality.

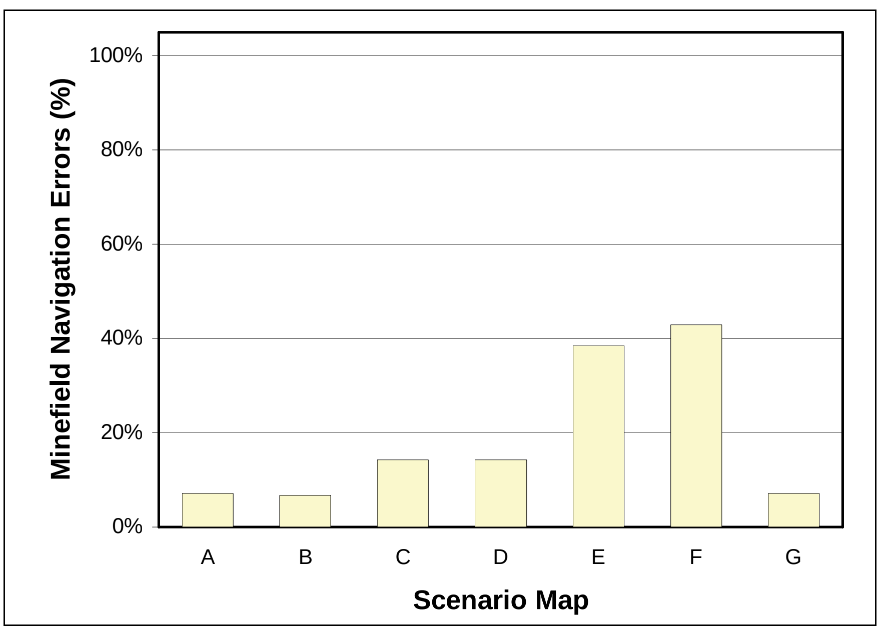

Figure 12. Minefield navigation errors versus scenario map.

In order to conduct the repeated measures ANOVA for navigation time, missing values had to be computed because of those scenarios that were not completed successfully (e.g., a fatal minefield navigation error was committed, thus ending the scenario). Four of a total of 98 scenarios (4.08%) had missing values which had to be replaced. Missing data were replaced with the series mean for each waypoint modality. Mean navigation time versus waypoint display modality is presented in figure 13.

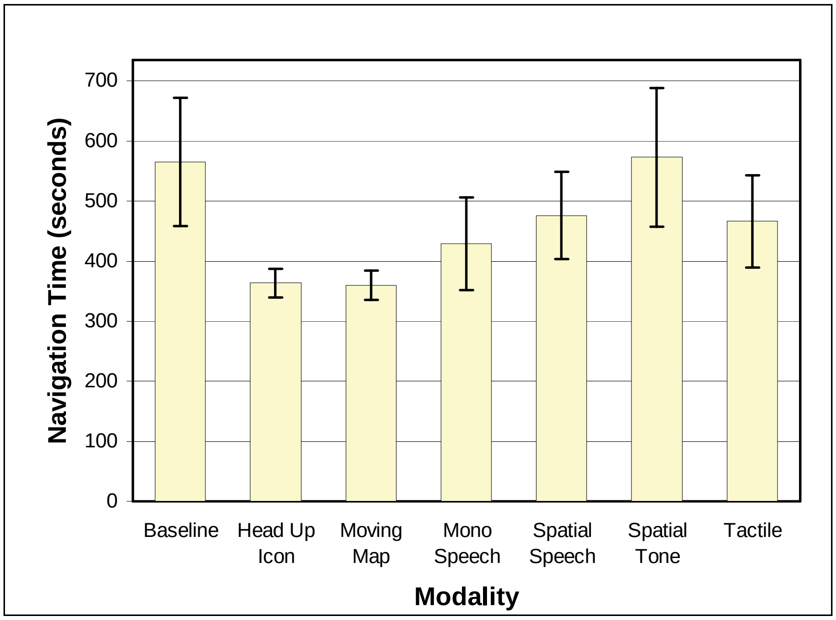

Figure 13. Mean navigation time versus waypoint display modality. (Error bars show 95% confidence interval.)

Significant differences existed between waypoint display modalities for navigation time, $F(6, 78) = 6.175$, $p < .001$. *Post hoc* analysis indicated that total navigation time was greater in the baseline modality than for the head-up icon, moving map, and monaural speech waypoint display modalities (all $p < .05$). Likewise, navigation time in the spatial audio tone modality was greater than the head-up icon, moving map, and monaural speech waypoint display modalities (all $p < .05$). Significant differences did not exist between the head-up icon, moving map, or monaural speech waypoint display modalities (all $p > .05$) or between the baseline, spatial speech, spatial tone, or tactile waypoint display modalities (all $p > .05$). A summary of navigation time mean differences is presented in table 4.

Table 4. Mean differences between modalities in navigation time.

Modality	Head-up Icon	Moving Map	Monaural Speech	Spatial Speech	Spatial Tone	Tactile
Baseline	**201.714 (p = .001)**	**205.571 (p = .001)**	**136.214 (p = .029)**	89.143 (p = .124)	-7.714 (p = .920)	99.000 (p = .108)
Head-up Icon		3.857 (p = .821)	-65.500 (p = .071)	**-112.571 (p = .005)**	**-209.429 (p = .002)**	**-102.714 (p = .006)**
Moving Map			-69.357 (p = .061)	**-116.429 (p = .004)**	**-213.286 (p = .002)**	**-106.571 (p = .019)**
Monaural Speech				-47.071 (p = .309)	**-143.929 (p = .032)**	-37.214 (p = .418)
Spatial Speech					-96.857 (p = .119)	9.857 (p = .790)
Spatial Tone						106.714 (p = .149)

Bold blocks indicate significant differences.

3.2.2 Situation Awareness

Mean overall SART and SART subscale scores versus waypoint display modality are presented in figures 14 and 15, respectively. Significant differences were found between waypoint display modalities for overall SART score, F (6, 78) = 5.496, p < .001. *Post hoc* analysis indicated that overall SART scores were greater (indicating a higher level of SA) in the moving map modality than the monaural speech, spatial speech, spatial tone, and tactile waypoint display modalities (all p < .05). Overall SART scores were lower in the spatial audio tone modality than all other waypoint display modalities (all p < .05). Significant differences did not exist between the baseline, head-up icon, or moving map waypoint display modalities (all p > .05). There were no significant differences between monaural speech and spatial speech waypoint display modalities (p = .372). A summary of SART score mean differences is presented in table 5.

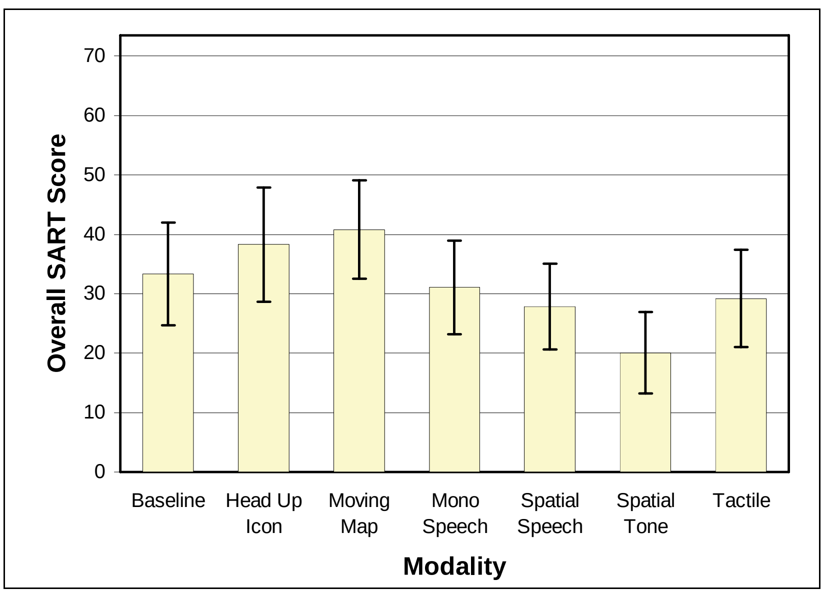

Figure 14. Overall SART score versus waypoint display modality. (Error bars show 95% confidence interval.)

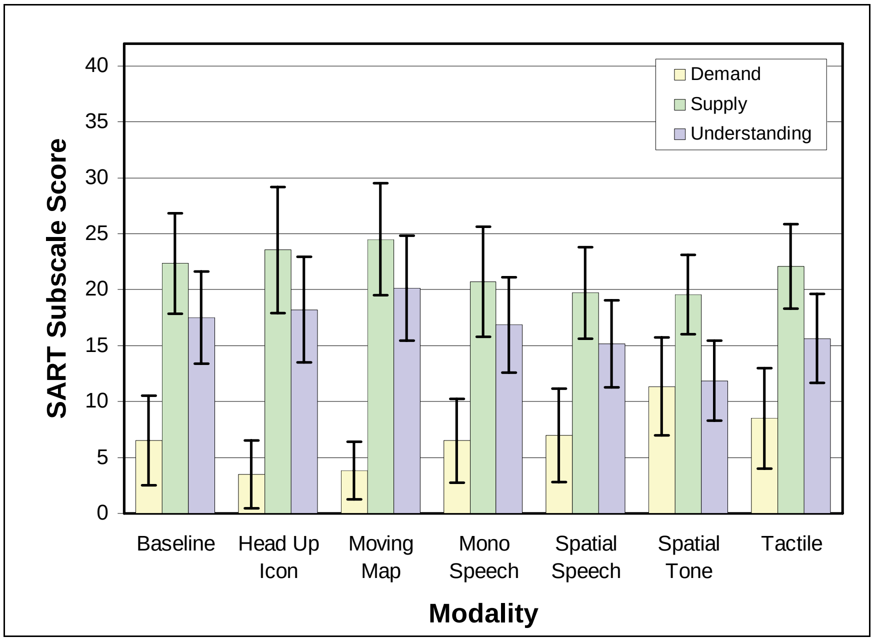

Figure 15. SART subscale scores versus waypoint display modality. (Error bars show 95% confidence interval.)

Table 5. Mean differences between modalities in SART score.

Modality	Head-up Icon	Moving Map	Monaural Speech	Spatial Speech	Spatial Tone	Tactile
Baseline	-4.929 (p = .222)	-7.429 (p = .059)	2.286 (p = .453)	5.500 (p = .303)	**13.286 (p = .036)**	4.143 (p = .405)
Head-up Icon		-2.500 (p = .200)	7.214 (p = .059)	10.429 (p = .065)	**18.214 (p = .009)**	9.071 (p = .134)
Moving Map			**9.714 (p = .005)**	**12.929 (p = .011)**	**20.714 (p = .002)**	**11.571 (p = .032)**
Monaural Speech				3.214 (p = .327)	**11.000 (p = .014)**	1.857 (p = .546)
Spatial Speech					**7.786 (p = .003)**	-1.357 (p = .674)
Spatial Tone						**-9.143 (p = .003)**

Bold blocks indicate significant differences.

Figure 15 illustrates the three SART subscale scores: demand, supply, and understanding. The repeated measures ANOVA revealed significant differences in the demand and understanding subscales but not the supply subscale. The results of the ANOVA are summarized in table 6. Results of *post hoc* analyses of SART subscale scores with significant differences are included in appendix C.

Table 6. Repeated measures ANOVA summary of SART subscale scores.

SART Subscale	F (6, 78)	Sig.
Demand	4.444	$p = .001$
Supply	1.793	$p = .111$
Understanding	5.594	$p < .001$

3.2.3 Mental Workload

Mean overall NASA-TLX score versus waypoint display modality is presented in figure 16. Significant differences were found between waypoint display modalities for overall NASA-TLX score, F (6, 78) = 7.445, $p < .001$. *Post hoc* analysis indicated that overall NASA-TLX scores were greater in the spatial tone modality than in the head-up icon, moving map, monaural speech, spatial speech, and tactile waypoint display modalities (all $p < .01$). Overall NASA-TLX scores were lower in both the head-up icon and moving map modalities than the baseline, monaural speech, and spatial tone waypoint display modalities (all $p < .05$). Significant differences did not exist between the baseline, monaural speech, spatial speech, or tactile waypoint display modali-ties (all $p > .05$). A summary of NASA-TLX score mean differences is presented in table 7.

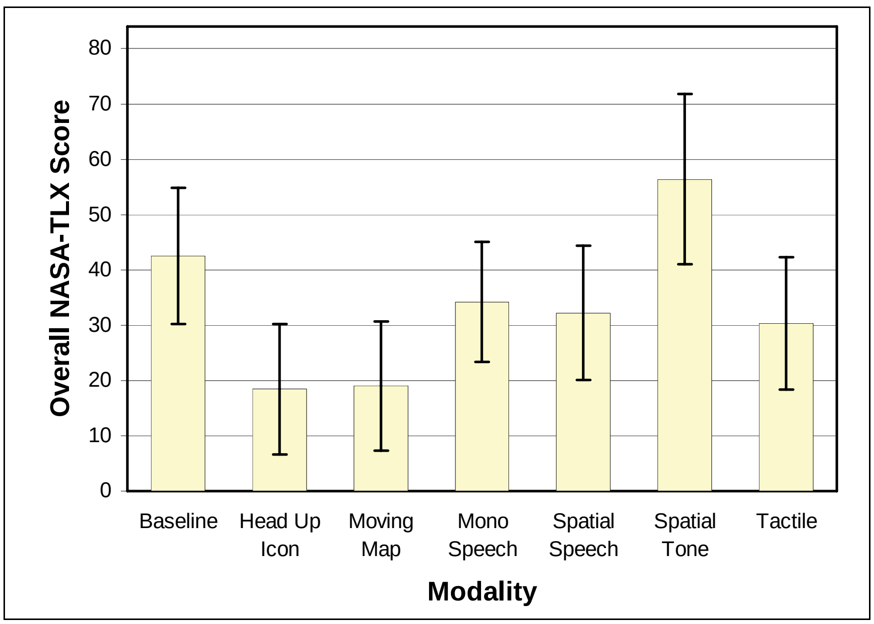

Figure 16. Overall NASA-TLX score versus waypoint display modality. (Error bars show 95% confidence interval.)

Table 7. Mean differences between modalities in NASA-TLX score.

Modality	Head-up Icon	Moving Map	Monaural Speech	Spatial Speech	Spatial Tone	Tactile
Baseline	**24.071 (*p* = .004)**	**23.500 (*p* = .002)**	8.286 (*p* = .153)	10.286 (*p* = .214)	-13.857 (*p* = .147)	12.214 (*p* = .163)
Head-up Icon		-0.571 (*p* = .899)	**-15.786 (*p* = .037)**	-13.785 (*p* = .071)	**-37.929 (*p* = .003)**	-11.857 (*p* = .126)
Moving Map			**-15.214 (*p* = .030)**	**-13.214 (*p* = .042)**	**-37.357 (*p* = .001)**	-11.286 (*p* = .123)
Monaural Speech				2.000 (*p* = .745)	**-22.143 (*p* = .009)**	3.929 (*p* = .540)
Spatial Speech					**-24.143 (*p* = .001)**	1.929 (*p* = .602)
Spatial Tone						**26.071 (*p* = .001)**

Bold blocks indicate significant differences.

Figure 17 illustrates the NASA-TLX subscale scores: mental demand, temporal demand, performance, effort, and frustration. An ANOVA revealed significant differences in all these subscales, except performance. The ANOVA results are summarized in table 8. *Post hoc* analyses of NASA-TLX subscale scores with significant differences are provided in appendix D.

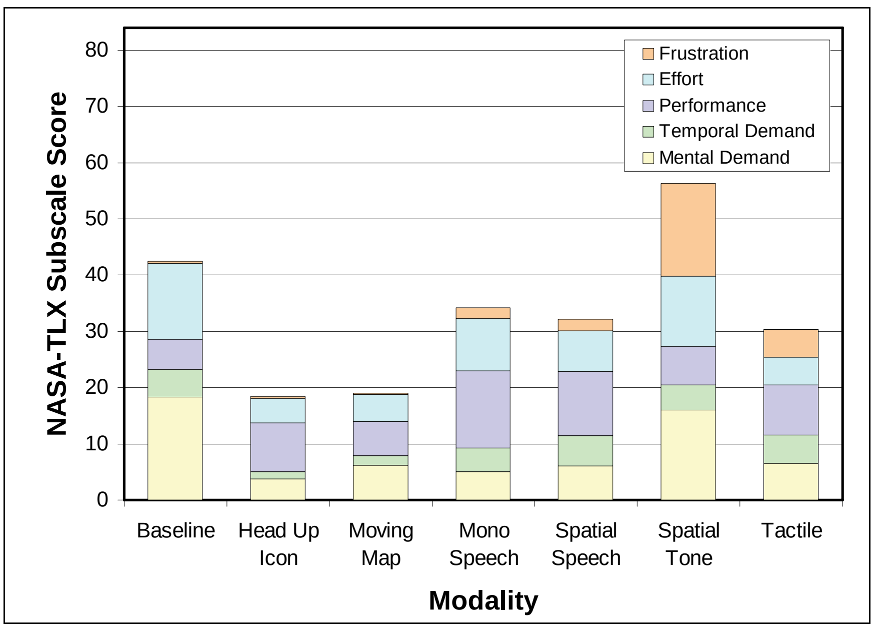

Figure 17. NASA-TLX subscale scores versus waypoint display modality.

Table 8. Repeated measures ANOVA summary of NASA-TLX subscale scores.

NASA-TLX Subscale	F (6, 78)	Sig.
Mental Demand	7.351	$p < .001$
Temporal Demand	3.675	$p = .003$
Performance	1.864	$p = .098$
Effort	6.333	$p < .001$
Frustration	8.850	$p < .001$

3.2.4 Modality Preference

Mean overall rating versus waypoint display modality for the modality evaluation questionnaire is presented in figure 18. Significant differences exist between waypoint display modalities for evaluation rating, F (6, 78) = 14.603, $p < .001$. *Post hoc* analysis indicated that evaluation ratings were lower in the spatial tone modality than all other waypoint display modalities (all $p < .01$). Evaluation ratings were higher for the moving map modality than for the baseline, spatial speech, spatial tone, and tactile waypoint display modalities (all $p < .05$). Significant differences did not exist between the head-up icon and moving map display modalities or the monaural speech and spatial speech waypoint display modalities (all $p > .25$). A summary of evaluation rating mean differences is presented in table 9.

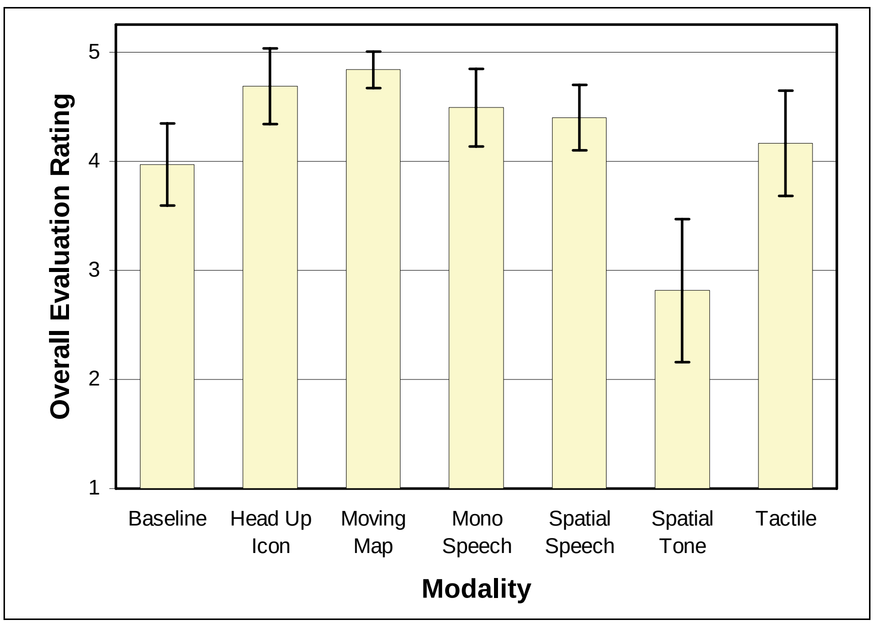

Figure 18. Modality evaluation rating versus waypoint display modality. (Error bars show 95% confidence interval.)

Table 9. Mean differences between modalities in evaluation rating.

Modality	Head-up Icon	Moving Map	Monaural Speech	Spatial Speech	Spatial Tone	Tactile
Baseline	**-0.714 (*p* = .010)**	**-0.867 (*p* < .001)**	**-0.520 (*p* = .011)**	-0.429 (*p* = .057)	**1.153 (*p* = .008)**	-0.194 (*p* = .517)
Head- up Icon		-0.153 (*p* = .254)	0.194 (*p* = .434)	0.286 (*p* = .273)	**1.867 (*p* < .001)**	0.520 (*p* = .109)
Moving Map			0.347 (*p* = .066)	**0.439 (*p* = .015)**	**2.020 (*p* < .001)**	**0.673 (*p* = .013)**
Monaural Speech				0.092 (*p* = .553)	**1.673 (*p* < .001)**	0.327 (*p* = .192)
Spatial Speech					**1.582 (*p* < .001)**	0.235 (*p* = .195)
Spatial Tone						**-1.347 (*p* < .001)**

Bold blocks indicate significant differences.

To further analyze the modality evaluation questionnaire, inter-item correlations (see table 10) and Chronbach's alpha were computed. Chronbach's alpha was calculated to be 0.933 for the scale.

Table 10. Inter-item correlations for the modality evaluation questionnaire.

Question Item	Efficient	Simple	Noticed	Attention	Helpful	Annoying
Effective	.891	.899	.703	.590	.823	.494
Efficient		.920	.661	.591	.753	.445
Simple			.710	.639	.824	.450
Noticed				.849	.771	.425
Attention					.745	.366
Helpful						.571

All correlations significant at the 0.01 level (2-tailed).

3.3 Discussion

The hypothesis that the alternate display modalities would provide greater navigation performance, increased SA, and decreased mental workload over the baseline display configuration is not fully supported by the results. There were no significant differences between the baseline and some of the alternate modalities for the navigation performance and mental workload dependent variables. For SA, an alternate modality (spatial tone) resulted in lower SA than the baseline modality, directly refuting the hypothesis.

The results of experiment 1 support the hypothesis that there would be significant differences between waypoint display modalities. Except for minefield navigation errors, all the dependent variables exhibited significant differences between display modalities. Results of the repeated measures ANOVA showed that minefield errors were affected by scenario map, but no other variables were affected by scenario map. Presentation order did not exhibit any significant effect on any of the dependent variables.

3.3.1 Navigation Performance

There were no statistically significant differences between modalities for minefield errors. However, between scenario maps, there were significant differences in minefield errors, with scenario maps “E” and “F” having 20% and 24% more errors, respectively, than the mean for all maps, indicating there was more than likely a problem with those two maps which caused more minefield errors. A potential confound to the results of minefield error is that the moving map and baseline modalities presented the participant with a complete and accurate view of the terrain via the navigation display, including the location of the minefield, whereas the other display modalities relied on the participant to perceive and react to the minefield markers as seen solely from the primary display. To be more fair to the different modalities, all scenarios should have included an additional, unmapped minefield or other additional hazard. Such a hazard would have prevented the participant from navigating solely by watching the moving map display.

Compared to the baseline modality, the head-up icon and moving map modalities took significantly less time to complete (both were 36% faster than the baseline). The monaural speech modality was significantly faster also, taking 24% less time than the baseline modality, while the spatial speech, spatial tone, and tactile modalities were not significantly different from the baseline modality.

3.3.2 Situation Awareness

The spatial tone waypoint display modality resulted in 40% lower SART scores, i.e., lower SA, than the baseline display modality. No modality exhibited significantly higher SART scores than the baseline display. Among the additional displays, the moving map waypoint display modality had significantly higher SART scores than the monaural speech, spatial speech, spatial tone, and tactile displays. The SART subscale analysis showed that although the supply subscale was relatively constant between display modalities, the demand and understanding subscales were significantly different between modalities.

3.3.3 Mental Workload

In experiment 1, both the head-up icon and moving map modalities resulted in significantly lower NASA-TLX scores (i.e., lower mental workload demand) than the baseline display modality by 57% and 56%, respectively. No modality exhibited significantly higher NASA-TLX scores than the baseline display. However, the spatial tone modality had significantly higher workload scores than the head-up icon, moving map, monaural speech, spatial speech, and tactile display modalities. The NASA-TLX subscale analysis showed that the mental demand, temporal demand, performance, effort, and frustration subscales were significantly different between modalities. The only subscale that showed significant differences was the performance subscale.

Although the NASA-TLX is not intended to measure absolute mental workload, it is interesting to note that the overall mean NASA-TLX score across all modalities is approximately 33 on a total scale of 100. This could imply that the designed navigation task, in general, places a low mental demand on the participant, contrary to the IMPRINT analyses by Mitchell et al. (2004). Further studies should be conducted with an increased mental workload, possibly including multiple simultaneous tasks.

3.3.4 Modality Preference

From the ANOVA of the modality evaluation ratings, it is evident that the moving map modality was preferred to the baseline, spatial speech, spatial tone, and tactile modalities and that the head-up icon modality was preferred to the baseline and spatial tone modalities. The spatial tone modality had the lowest evaluation rating of all the modalities. The high internal consistency, as measured by Chronbach's alpha, is a good indication that the seven question items of the designed questionnaire were measuring the same dimension.

3.3.5 Summary

From the *post hoc* analyses of each dependent variable, it is clear that the head-up icon and moving map were the two consistently best display modalities. These two display modalities presented information visually in a way that is more intuitive with much less mental calculation than the baseline modality. In agreement with MRT, the visually oriented task of navigation, using a visual display that enables ease of understanding information, allows for improved performance.

Across all the dependent variables, there were no significant differences between the monaural and spatial speech modalities. However, no additional auditory tasks were included in the experiment. It could be that at the low level of auditory demand for this navigation task, there is not the anticipated improvement that spatial audio can afford.

The spatial tone modality showed poor results across all dependent variables in experiment 1, most apparently in the modality evaluation and NASA-TLX results. Examining the NASA-TLX subscales revealed that the frustration subscale score is markedly higher than all other modalities for the spatial tone display modality. The spatial tone modality received much higher scores for the "annoying" question item of the modality evaluation questionnaire. It is believed that the extreme annoyance of the spatial tone could have caused the participants to rate scores lower across the other dependent variables.

4. Experiment 2

4.1 Method

4.1.1 Participants

The participants for the second experiment were 18 male Soldiers, ranging in age from 18 to 29 years (M = 22.3 years, SD = 3.32 years). Participants had from 0.5 to 9.5 years of military service (M = 3.65 years, SD = 2.61 years). Participants were from a diverse range of MOSs. All the participants had normal visual acuity and color vision in both eyes. Participants were not given a hearing threshold level test, but all participants reported no suspected hearing loss or damage. The voluntary, fully informed consent of the persons used in this research was obtained as required by 32 CFR 219 and AR 70-25. The investigator has adhered to the policies for the protection of human subjects, as prescribed in AR 70-25.

4.1.2 Apparatus

As in the first experiment, participants sat at a computer workstation with two PCs equipped identically to those in the first experiment except that a Sennheiser HD 280 Pro circumaural stereo headset was used to provide audio from the PC. VBS1 was again used as the virtual environment for experiment 2.

4.1.3 Task

Similar to the first experiment, each navigation scenario consisted of a series of three waypoints, each including a visible object. The navigation mission consisted of three segments, each a 2-km distance. Two of the three navigation segments included identifying and navigating around a 200-m by 1000-m minefield marked with danger signs around the perimeter. One of the minefields was identified on the navigation map (in the baseline and moving map display modalities), and the other minefield was intentionally not identified on the navigation map to force the participant to pay attention to the primary display and not solely rely on the navigation display. Diagrams of the six scenario maps are included in appendix E. Scripting of the scenarios in VBS1 was greatly improved for this experiment.

4.1.4 Questionnaires

The same questionnaires as the first experiment were used: the SART, NASA-TLX, and modality evaluation questionnaires.

4.1.5 Experimental Design

Experiment 2 was also a single factor within-subjects design. The independent and dependent variables were the same as for the first experiment; waypoint display modality was again the independent variable, while navigation performance, SA, mental workload, and modality preference remained the dependent variables. The same measures were used for each dependent variable as in the first experiment.

For experiment 2, there were six levels of the waypoint display modality independent variable: baseline, head-up icon, moving map, monaural speech, spatial speech, and tactile. The spatial audio tone modality was removed for this experiment because of the poor results of the modality in the first experiment. The baseline, head-up icon, and moving map conditions were identical as those used in experiment 1. The only difference in the monaural speech, spatial speech, and tactile conditions was that direction cues were given every 10 seconds rather than every 100 meters traveled. Each condition is now described in more detail.

- **Baseline** – A static, 2-D overhead map provided on the navigation display showed the starting position, waypoint locations, GPS grid lines, terrain features, and landmarks but did not update or show the location or heading of the vehicle (see figure 5). The participant used the primary display along with the GPS display (in standard UTM format) and compass to determine his current location and heading to the next waypoint. Close views of the GPS display and compass display areas are presented in figures 6 and 7, respectively.

- **Head-up icon** – A yellow, square icon was overlaid on the primary display indicating the location of the waypoint (see figure 8). When the waypoint was out of the driver's FOV, the icon changed to a triangular arrow, indicating the direction toward the waypoint. The word "waypoint" and the distance to the waypoint were shown next to the icon.

- **Moving map** – A 2-D overhead map provided on the navigation display showed the starting position, waypoint locations, GPS coordinates, terrain features, and landmarks, exactly the same as the baseline condition, but also showed the location of the vehicle updated in real time (see figure 9). The vehicle icon was at the center of the map and rotated to show heading, while the map translated up/down/left/right to show position.

- **Monaural speech** – Every 10 seconds, a synthetic speech voice (generated with the AT&T Natural Voices Text-to-Speech Engine) announced the relative direction to the next waypoint (e.g., "waypoint at 10 o'clock"). Distance to the next waypoint was communicated by the same synthetic speech voice, at designated distance intervals of 1000, 500, 400, 300, 200, and 100 meters from the waypoint (e.g., "400 meters to waypoint"). The heading and distance information was presented at equal loudness to both ears.

- **Spatial speech** – Emersys Maven 3D Professional was used to create spatial audio sound representa-tions of the same synthetic speech voice used in the monaural speech condition. The software uses a generic head-related transform function to produce a stereo sound representation of monaural sounds. Every 10 seconds, the synthetic speech voice announced the relative direction to the next waypoint which appeared to emanate from the direction of the next waypoint (e.g., "waypoint at 1 o'clock" is heard from the 30-degree azimuth). Distance was presented in the same manner as the monaural speech condition.

- **Tactile** – The MIT WTCU (see figure 10) was used with 12 vibro-tactile motors positioned at the 12 clock positions in a belt worn around the participant's abdomen. Every 10 seconds, the WTCU provided two 1000-ms bursts with a 333-ms rest in the relative direction to the next waypoint (e.g., if the next waypoint was at 3 o'clock, the stimulus vibrated at the participant's right side). The vibro-tactile motors used vibrated at approximately 70 Hz. Distance was presented in the same manner as the monaural speech modality.

The navigation display was only provided for the baseline and moving map conditions. For all the conditions, when a waypoint was reached, the synthetic speech voice announced "waypoint reached". All the generated sound files (synthetic speech and spatial synthetic speech) were normalized to 98% of maximum volume with Adobe Audition.

We created a Greco-Latin square design by superimposing two balanced Latin squares, one for the display modality condition, and one for the navigation map (see table 11). The number and letter combination in each cell of table 11 indicates the scenario that was used for each participant; the display modality (1-6) is shown first, and the scenario map (A-F) is shown second. Because of the nature of the 6 x 6 Greco-Latin square, it was impossible to counterbalance both presentation order and scenario map, so a design was chosen that balanced modality and scenario map, sacrificing the balancing of scenario map and presentation order.

Table 11. Greco-Latin square design for experiment 2.

		Order					
		1st	**2nd**	**3rd**	**4th**	**5th**	**6th**
Participant Number	**1, 7, 13**	1A	2B	6C	3D	5E	4F
	2, 8, 14	2A	3B	1C	4D	6E	5F
	3, 9, 15	3A	4B	2C	5D	1E	6F
	4, 10, 16	4A	5B	3C	6D	2E	1F
	5, 11, 17	5A	6B	4C	1D	3E	2F
	6, 12, 18	6A	1B	5C	2D	4E	3F

4.1.6 Procedure

Volunteers received an overview of the experiment and details of the procedures and were informed of any risks involved in their participation. The volunteers read aloud and were asked to sign an informed consent form if they agreed to participate. After their fully informed, voluntary consent was obtained, participants completed a demographics questionnaire, visual acuity test, and a color deficiency test.

Each participant received 2 hours' training and practice with VBS1. First, participants were familiarized with VBS1, focusing on the controls via the keyboard and mouse. Participants then completed practice scenarios for each of the six experimental conditions, each lasting approximately 10 minutes. Participants also received instructions and practiced completing the NASA-TLX, SART, and modality evaluation questionnaires after the final practice scenario.

After training was complete, participants completed the six experimental conditions. Before each scenario, the participants received a short briefing reminding them of the visible markers at the waypoints; they were told to be aware of and navigate around the minefields and were told to reach each of the waypoints as quickly as possible. After completing each experimental condition, the participant completed the NASA-TLX, SART, and modality evaluation questionnaires.

4.2 Results

SPSS for Windows, Release 13, was again used for statistical analysis. Each dependent variable was analyzed for significant differences between waypoint display modalities with a repeated measures ANOVA. Additionally, a separate repeated measures ANOVA was conducted with scenario map and order as the independent variable. Order and scenario map could not be tested individually since scenario map and order were the same in each condition. When significant differences were present ($\alpha < .05$), *post hoc* tests were performed with the LSD method. There were significant effects of waypoint display modality for all but one dependent variable and no significant effects of scenario map and order on any of the dependent variables. A summary of the repeated measures ANOVA results for modality and scenario map and order is presented in tables 12 and 13, respectively.

Table 12. Repeated measures ANOVA summary, waypoint display modality as independent variable.

Dependent Variable	F (5, 85)	Sig.
Minefield Navigation Error	0.722	$p = .609$
Navigation Time	12.304	$p < .001$
Situation Awareness (SART)	2.520	$p = .035$
Mental Workload (NASA-TLX)	8.239	$p < .001$
Modality Rating	7.291	$p < .001$

Table 13. Repeated measures ANOVA summary, scenario map and order as independent variable.

Dependent Variable	F (5, 85)	Sig.
Minefield Navigation Error	1.811	$p = .119$
Navigation Time	0.991	$p = .428$
Situation Awareness (SART)	1.262	$p = .288$
Mental Workload (NASA-TLX)	0.930	$p = .466$
Modality Preference	0.929	$p = .467$

4.2.1 Navigation Performance

Two metrics were again used for navigation performance: minefield navigation errors and navigation time. In this experiment, there were two types of minefields: mapped and unmapped. This distinction is only relevant to the baseline and moving map modalities since those were the only modalities that provided the navigation display (for the other modalities, all the minefields are essentially "unmapped" since there is no navigation display to show a map).

The percentage of minefield navigation errors versus waypoint display modality is presented in figure 19, with stacked bars representing mapped and unmapped minefield navigation errors. From the repeated measures ANOVA, no significant differences were found between waypoint display modalities for minefield navigation errors.

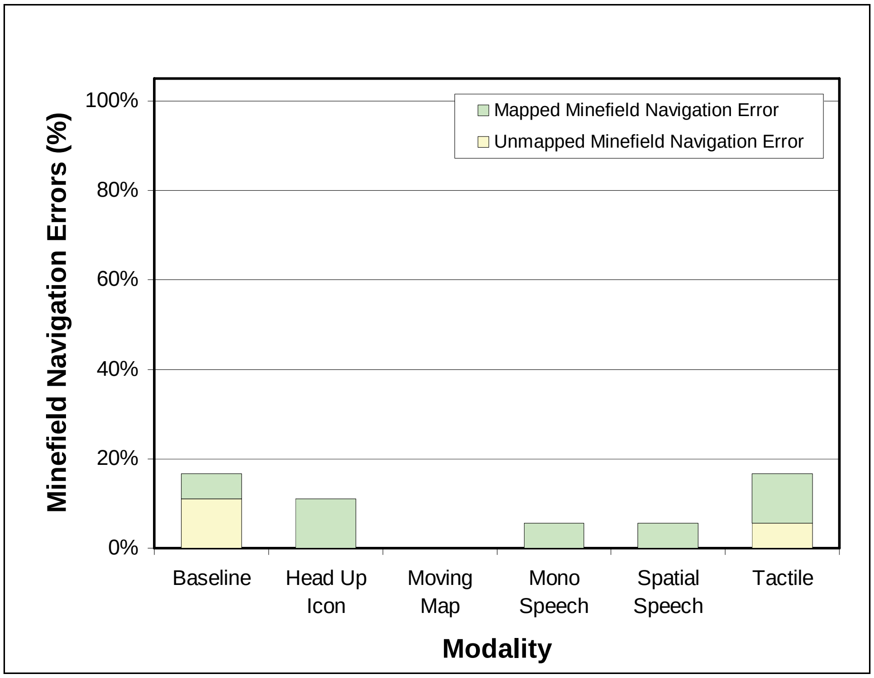

Figure 19. Minefield navigation errors versus waypoint display modality.

Although no significant differences were identified between scenario map/order for minefield navigation errors, the significance level for scenario map/order was much greater than for waypoint display modality ($p = .119$, $p = .609$, respectively). Figure 20 presents the percentage of minefield navigation errors versus scenario map.

Unlike experiment 1, there were no missing values to be computed. Two extreme data outliers were identified for navigation time; however, after different data outlier strategies were weighted, the outliers were left unchanged in the data. Mean navigation time versus waypoint display modality is presented in figure 21. Significant differences existed between waypoint display modalities for navigation time, F (5, 85) = 12.304, $p < .001$. *Post hoc* analysis indicated that total navigation time was greater (i.e., slower) in the baseline modality than all other waypoint display modalities (all $p < .01$). Navigation time in the moving map modality was less (i.e., faster) than the baseline, monaural speech, spatial speech, and tactile waypoint display modalities (all $p < .01$). Navigation time in the head-up icon modality was less (i.e., faster) than the baseline, spatial speech, and tactile waypoint display modalities (all $p < .01$). Significant differences did not exist between the head-up icon and moving map, or the monaural speech, spatial speech, and tactile waypoint display modalities (all $p > .05$). A summary of navigation time mean differences is presented in table 14.

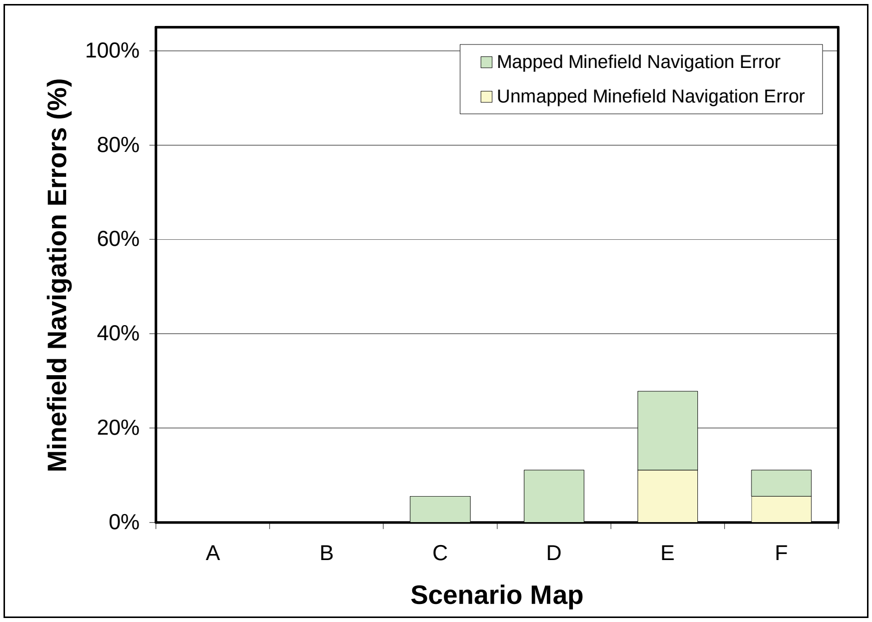

Figure 20. Minefield navigation errors versus waypoint display modality.

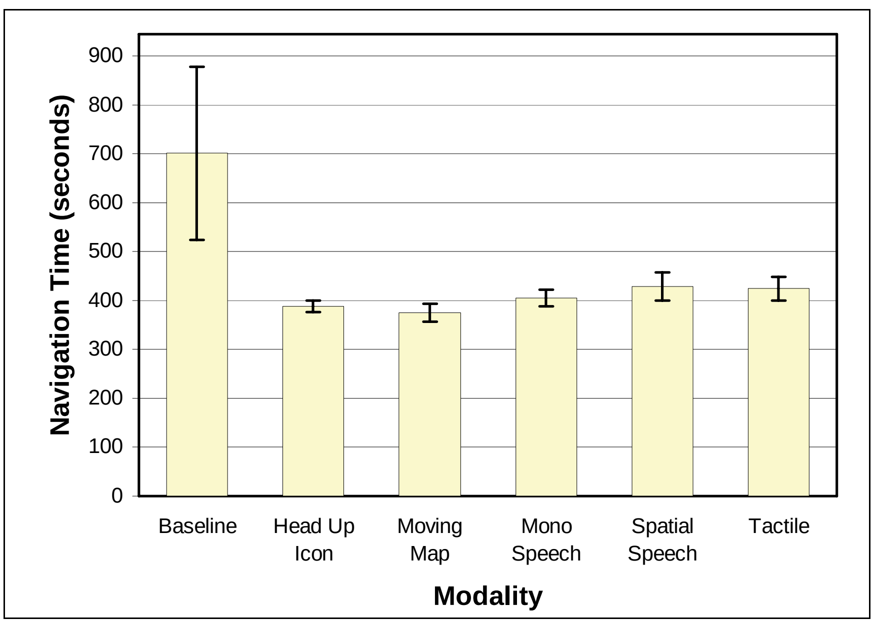

Figure 21. Mean navigation time versus waypoint display modality. (Error bars show 95% confidence interval.)

Table 14. Mean differences between modalities in navigation time.

Modality	Head-up Icon	Moving Map	Monaural Speech	Spatial Speech	Tactile
Baseline	**313.838 (p = .002)**	**326.889 (p = .001)**	**297.056 (p = .002)**	**272.944 (p = .005)**	**277.278 (p = .006)**
Head-Up Icon		13.056 (p = .233)	-16.778 (p = .082)	**-40.889 (p = .010)**	**-36.556 (p = .007)**
Moving Map			**-29.833 (p = .002)**	**-53.944 (p < .001)**	**-49.611 (p < .001)**
Monaural Speech				-24.111 (p = .056	-19.778 (p = .157)
Spatial Speech					4.333 (p = .765)

Bold blocks indicate significant differences.

4.2.2 Situation Awareness

Mean overall SART score versus waypoint display modality is presented in figure 22. Marginally significant differences were found between waypoint display modalities for overall SART score, F (5, 85) = 2.520, p = .035. *Post hoc* analysis indicated that overall SART scores were lower (indicating a lower level of SA) in the tactile modality than the baseline, moving map, and spatial speech waypoint display modalities (all p < .05). Significant differences did not exist between the baseline, head-up icon, moving map, monaural speech, or spatial speech waypoint display modalities (all p > .05). A summary of SART score mean differences is presented in table 15.

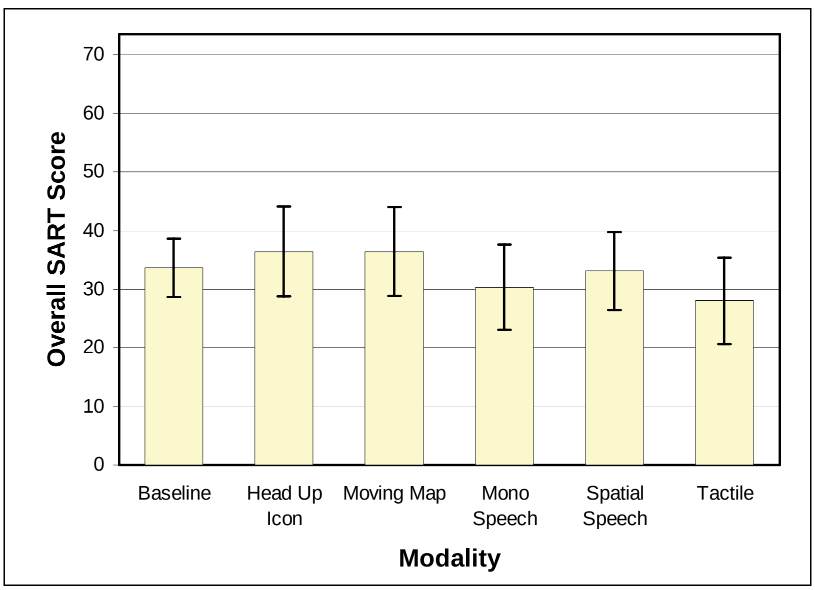

Figure 22. Overall SART score versus waypoint display modality. (Error bars show 95% confidence interval.)

Table 15. Mean differences between modalities in SART score.

Modality	Head-up Icon	Moving Map	Monaural Speech	Spatial Speech	Tactile
Baseline	-2.833 (p = .374)	-2.833 (p = .393)	3.278 (p = .177)	0.500 (p = .803)	**5.556 (p = .033)**
Head- Up Icon		0.000	6.111 (p = .153)	3.333 (p = .296)	8.389 (p = .060)
Moving Map			6.111 (p = .106)	3.333 (p = .288)	**8.389 (p = .048)**
Monaural Speech				-2.778 (p = .232)	2.278 (p = .157)
Spatial Speech					**5.056 (p = .047)**

Bold blocks indicate significant differences.

Figure 23 illustrates the three SART subscale scores (demand, supply, and understanding) versus display modality. The repeated measures ANOVA revealed significant differences only in the demand subscale. The supply and understanding subscales did not reveal any significant differences for display modality. The results of the ANOVA are summarized in table 16. Results of *post hoc* analyses of SART subscale scores with significant differences are included in appendix F.

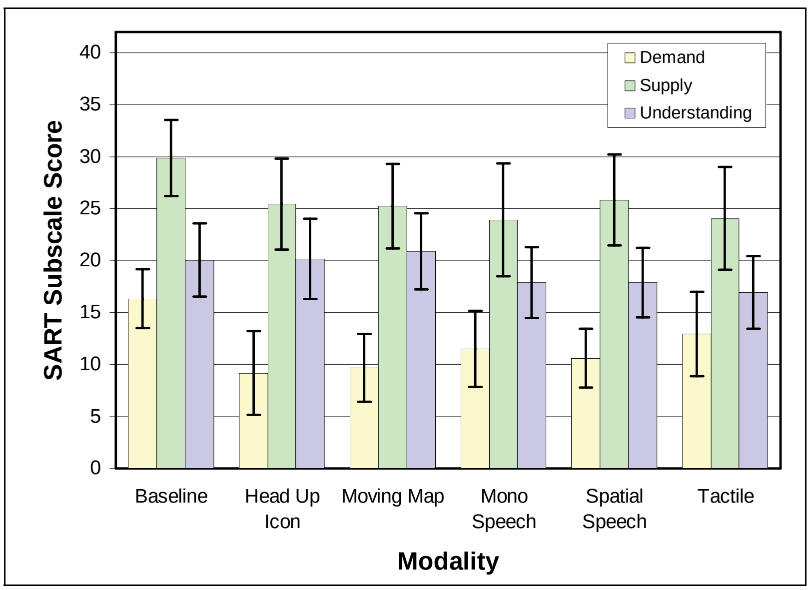

Figure 23. SART subscale scores versus waypoint display modality. (Error bars show 95% confidence interval.)

Table 16. Repeated measures ANOVA summary of SART subscale scores.

SART Subscale	F (5, 85)	Sig.
Demand	5.649	$p < .001$
Supply	2.294	$p = .052$
Understanding	2.122	$p = .070$

4.2.3 Mental Workload

Mean overall NASA-TLX score versus waypoint display modality is presented in figure 24. Significant differences were found between waypoint display modalities for overall NASA-TLX score, F (5, 85) = 8.239, $p < .001$. *Post hoc* analysis indicated that overall NASA-TLX scores were greater (indicating higher workload) in the baseline modality than all other waypoint display modalities (all $p < .05$). Overall NASA-TLX scores were lower (indicating lower workload) in the head-up icon modality than the baseline, spatial speech, and tactile waypoint display modalities (all $p < .05$). Significant differences did not exist between the head-up icon, moving map, or monaural speech modalities (all $p > .05$), nor did significant differences exist between the moving map, monaural speech, spatial speech, and tactile modalities (all $p > .05$). A summary of NASA-TLX score mean differences is presented in table 17.

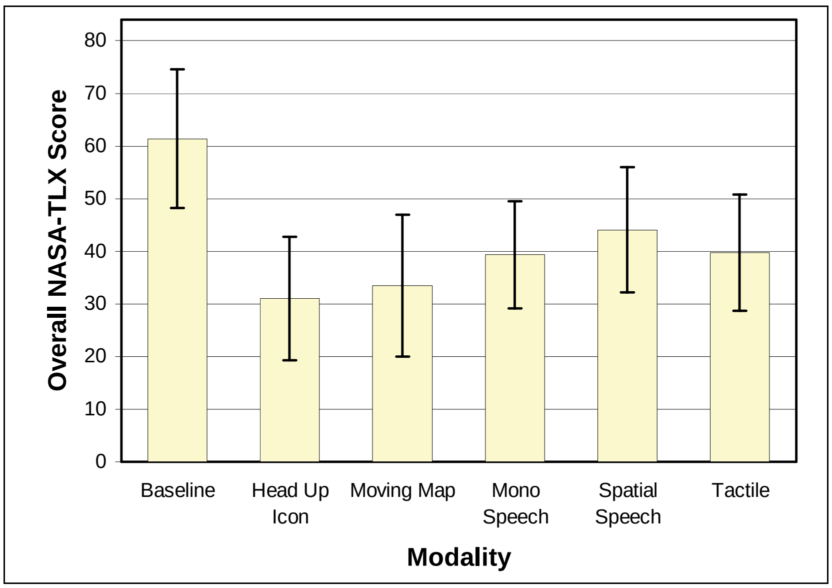

Figure 24. Overall NASA-TLX score versus waypoint display modality.
(Error bars show 95% confidence interval.)

Table 17. Mean differences between modalities in NASA-TLX score.

Modality	Head-up Icon	Moving Map	Monaural Speech	Spatial Speech	Tactile
Baseline	**30.389 (p = .001)**	**27.889 (p = .003)**	**22.056 (p = .001)**	**17.333 (p = .017)**	**21.667 (p = .003)**
Head-Up Icon		-2.500 (p = .513)	-8.333 (p = .087)	**-13.056 (p = .007)**	**-8.722 (p = .045)**
Moving Map			-5.833 (p = .242)	-10.556 (p = .087)	-6.222 (p = .264)
Monaural Speech				-4.722 (p = .132)	-0.389 (p = .931)
Spatial Speech					4.333 (p = .258)

Bold blocks indicate significant differences.

Figure 25 illustrates the NASA-TLX subscale scores (mental demand, temporal demand, performance, effort, and frustration) versus display modality. An ANOVA revealed significant differences in the mental demand and effort subscales but not the temporal demand, performance, or frustration subscales. The ANOVA results are summarized in table 18. *Post hoc* analyses of NASA-TLX subscale scores with significant differences are included in appendix G.

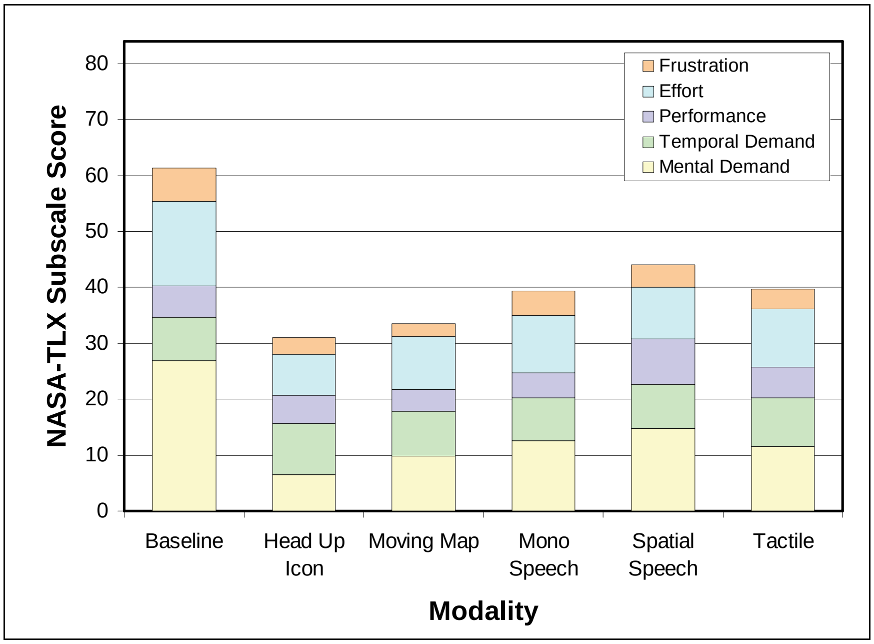

Figure 25. NASA-TLX subscale scores versus waypoint display modality.

Table 18. Repeated measures ANOVA summary of NASA-TLX subscale scores.

NASA-TLX Subscale	F (5, 85)	Sig.
Mental Demand	15.309	$p < .001$
Temporal Demand	0.185	$p = .968$
Performance	0.899	$p = .486$
Effort	2.881	$p = .019$
Frustration	0.590	$p = .708$

4.2.4 Modality Preference

Mean overall participant evaluation rating versus waypoint display modality for the modality evaluation questionnaire is presented in figure 26. The repeated measures ANOVA revealed significant differences between waypoint display modalities for evaluation rating, F (5, 85) = 7.291, $p < .001$. *Post hoc* analysis indicated that evaluation ratings were lower in the baseline modality than all other waypoint display modalities (all $p < .05$). Evaluation ratings were higher for the head-up icon modality than the baseline, monaural speech, and tactile waypoint display modalities (all $p < .05$). Significant differences did not exist between the head-up icon, moving map, and spatial speech display modalities, or the moving map, monaural speech, spatial speech, and tactile waypoint display modalities (all $p > .05$). A summary of evaluation rating mean differences is presented in table 19.

To further analyze the modality evaluation questionnaire, inter-item correlations (table 20) and Chronbach's alpha were computed. Chronbach's alpha was calculated to be 0.859 for the scale.

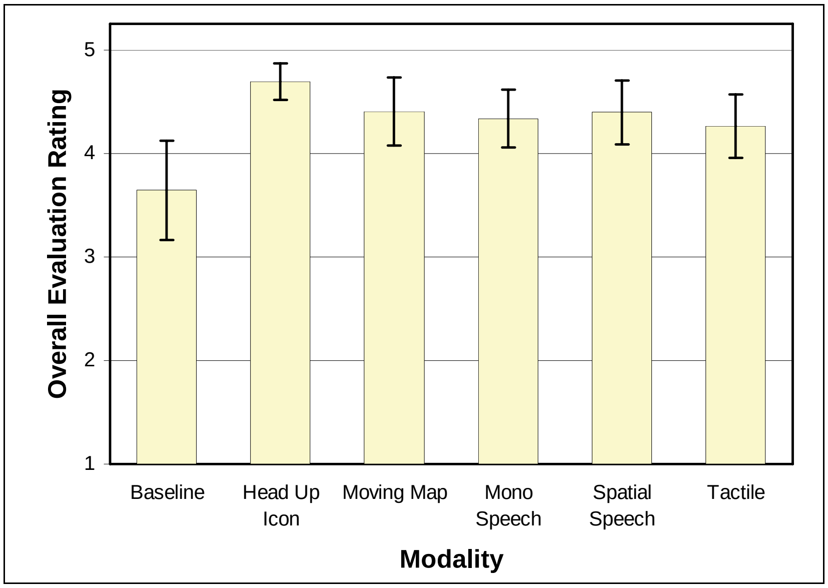

Figure 26. Participant evaluation rating versus waypoint display modality. (Error bars show 95% confidence interval.)

Table 19. Mean differences between modalities in evaluation rating.

Modality	Head-up Icon	Moving Map	Monaural Speech	Spatial Speech	Tactile
Baseline	**-1.048 (p = .001)**	**-0.762 (p = .014)**	**-0.690 (p = .009)**	**-0.754 (p = .004)**	**-0.619 (p = .014)**
Head-Up Icon		0.286 (p = .082)	**0.357 (p = .012)**	0.294 (p = .098)	**0.426 (p = .009)**
Moving Map			0.071 (p = .572)	0.008 (p = .948)	0.143 (p = .457)
Monaural Speech				-0.063 (p = .505)	0.071 (p = .519)
Spatial Speech					0.135 (p = .387)

Bold blocks indicate significant differences.

Table 20. Inter-item correlations for the modality evaluation questionnaire.

Question Item	Efficient	Simple	Noticed	Attention	Helpful
Effective	.811	.811	.582	.627	.387
Efficient		.766	.621	.729	.344
Simple			.629	.714	.408
Noticed				.839	.423
Attention					.483

All correlations significant at the 0.01 level (2-tailed).

4.3 Discussion

The hypothesis that the alternate display modalities would provide greater navigation performance, increased SA, and decreased mental workload than the baseline display configuration is not fully supported by the results. There were no significant differences between the baseline and several of the alternate modalities for the SA dependent variables or an alternate modality (tactile) that resulted in lower SA than the baseline modality, which directly refutes the hypothesis.

The results of experiment 2 support the hypothesis that there would be significant differences between waypoint display modalities. Except for minefield navigation errors, all the dependent variables exhibited significant differences between display modalities.

4.3.1 Navigation Performance

There were no statistically significant differences between modalities for minefield errors. Results of the repeated measures ANOVA did not show that minefield errors were affected by scenario map and order, but the significance level was much greater for scenario map and order than for waypoint display modality (p = .119, p = .609, respectively), indicating there was more likely an effect because of scenario map/order than display modality.

To address the minefield navigation error problem identified in experiment 1, the navigation scenarios in experiment 2 included both a mapped and unmapped minefield (this distinction is only relevant to the baseline and moving map modalities). Examining the differences between the mapped and unmapped minefield navigation errors in the baseline display modality showed that there was not a significant difference in a paired sample T test (p = .331). There were no minefield navigation errors for the moving map modality, so there was no comparison for that modality.

Compared to the baseline modality, all the modalities took significantly less time to complete. Fastest were the head-up icon and moving map modalities which were 45% and 47% faster than baseline, respectively. The monaural speech, spatial speech and tactile modalities were significantly faster also, taking 42%, 39%, and 40% less time than the baseline modality.

4.3.2 Situation Awareness

In experiment 2, there were marginally significant differences in overall SART scores between waypoint modalities. *Post hoc* comparison revealed differences between only the tactile and baseline, moving map, and spatial speech modalities. The tactile display may have generated lower SART scores because of the difference in information quantity given by the visual displays. The tactile display, monaural and spatial speech auditory displays facilitate a local awareness of the environment, rather than the global picture that the visual displays enable. Combining displays into a multimodal interface would be worth investigation. The SART subscale analysis showed that the demand subscale was significantly different between modalities while the supply and understanding subscales were relatively constant between display modalities.

4.3.3 Mental Workload

As in the first experiment, both the head-up icon and moving map modalities resulted in significantly lower NASA-TLX scores (i.e., lower mental workload demand) than the baseline display modality by 50% and 45%, respectively. All modalities in experiment 2 resulted in significantly lower NASA-TLX scores than the baseline: monaural speech by 36%, spatial speech by 28%, and tactile by 35%. The NASA-TLX subscale analysis showed that the mental demand, perform-ance, and effort subscales were significantly different between modalities. The mental demand subscore was much higher in the baseline display modality because of the mental calculation required to determine the appropriate course to the waypoint when no automated guidance is provided.

The overall mean NASA-TLX score across all modalities for experiment 2 was approximately 42 on a total scale of 100. As mentioned for experiment 1, the NASA-TLX is not intended to measure absolute mental workload; however, this could imply that the navigation task in this experiment (which was nearly identical to the task in experiment 1) places a low mental demand on the participant. Again, further investigation into navigation tasks with an increased mental workload should be conducted to assess the effects of display modality in a more demanding task.

4.3.4 Modality Preference

From the ANOVA of the modality evaluation ratings, it is evident that the moving map modality was preferred to the baseline modality and that the head-up icon modality was preferred to the baseline, monaural speech, and tactile modalities. The baseline modality had the lowest evaluation rating of all the modalities. As in experiment 1, the modality preference questionnaire exhibited high internal consistency, as measured by Chronbach's alpha. Again, this is a good indication that the seven question items of the designed questionnaire were measuring the same dimension.

4.3.5 Summary

Similar to experiment 1, the *post hoc* analyses of each dependent variable revealed that the head-up icon and moving map were the two consistently best display modalities for experiment 2. These two display modalities presented information visually in a way that is more intuitive with much less mental calculation than the baseline modality. In agreement with MRT, the visually oriented task of navigation, which used a visual display that enabled ease of understanding information, allows for improved performance.

In experiment 2, just as in the first experiment, there were no significant differences between the monaural and spatial speech modalities across all the dependent variables. As previously mentioned, no additional auditory tasks were included in the experiment. One explanation is that with the low level of auditory demand for this navigation task, there was not the anticipated improvement that spatial audio would allow.

Like the first experiment, the tactile display modality was not significantly different than the monaural speech or spatial speech modalities (except for marginal difference between the tactile and spatial speech modality in overall SART scores). It would be interesting to see if in a higher workload environment, especially one with high auditory demand, the tactile display would result in improved performance.

5. Conclusions

The results of these experiments indicate that the standard method of navigation, represented by the baseline display modality, which provides a static map and forces the driver to determine the appropriate course to take, is time consuming and mentally demanding. The augmented visual displays, represented by the head-up icon and moving map displays, significantly reduced navigation time, maintained SA, and drastically reduced mental workload over the baseline display.

The effect of channel off loading, changing the display modality from visual to auditory or tactile, has not resulted in improved performance in these experiments, perhaps because of the low task demand presented. Future research should increase the overall task demand by increasing the visual and auditory demands significantly. Additional tasks including visual search for targets and communications monitoring, which are significant real-life factors increasing the mental demands of tactical vehicle drivers, should be considered.

6. References

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Appendix A. Scenario Maps (Experiment 1)

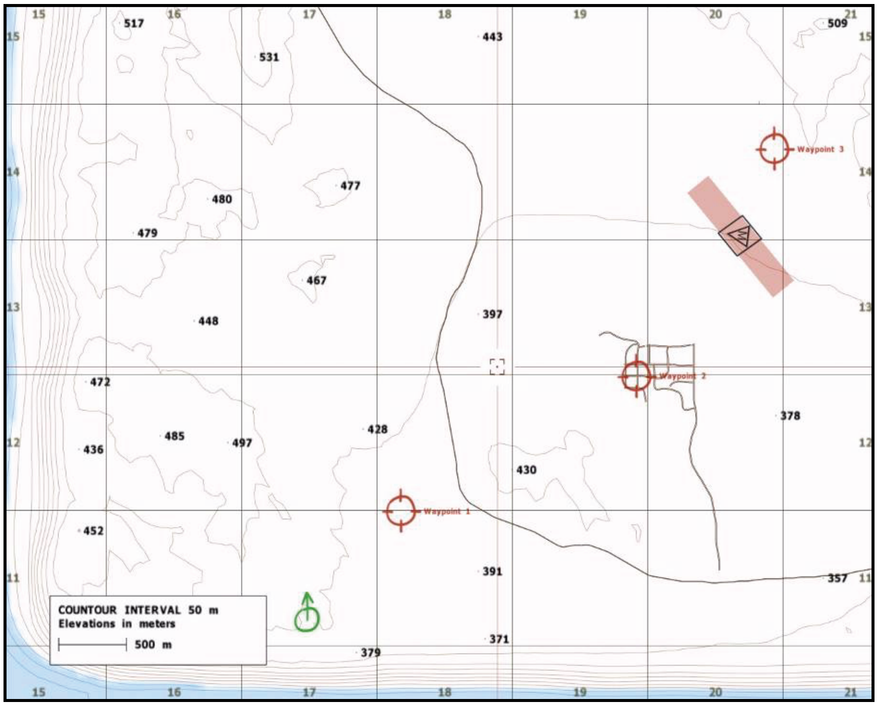

Figure A-1. Map A.

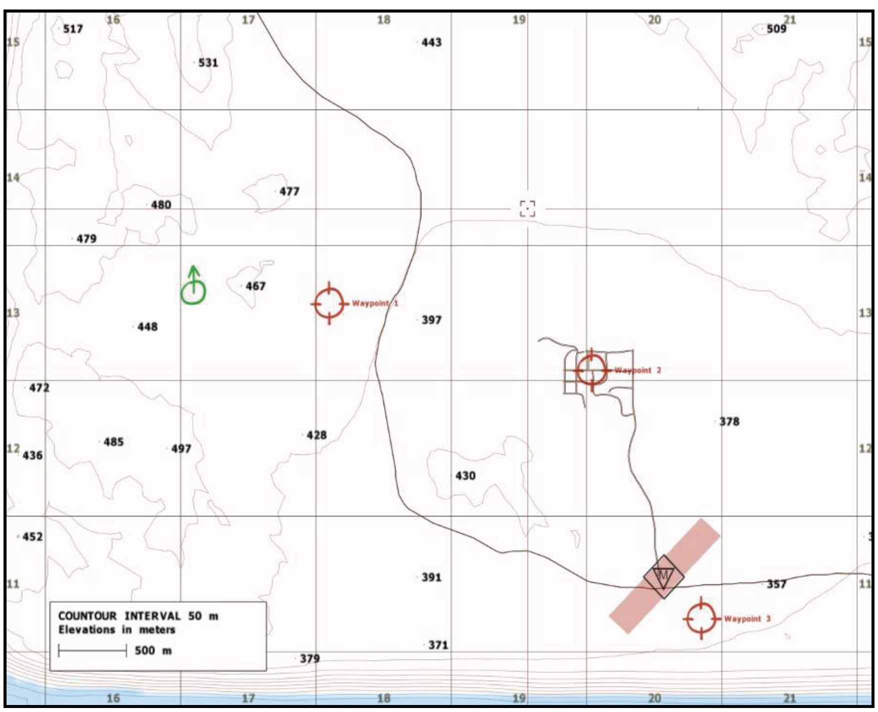

Figure A-2. Map B.

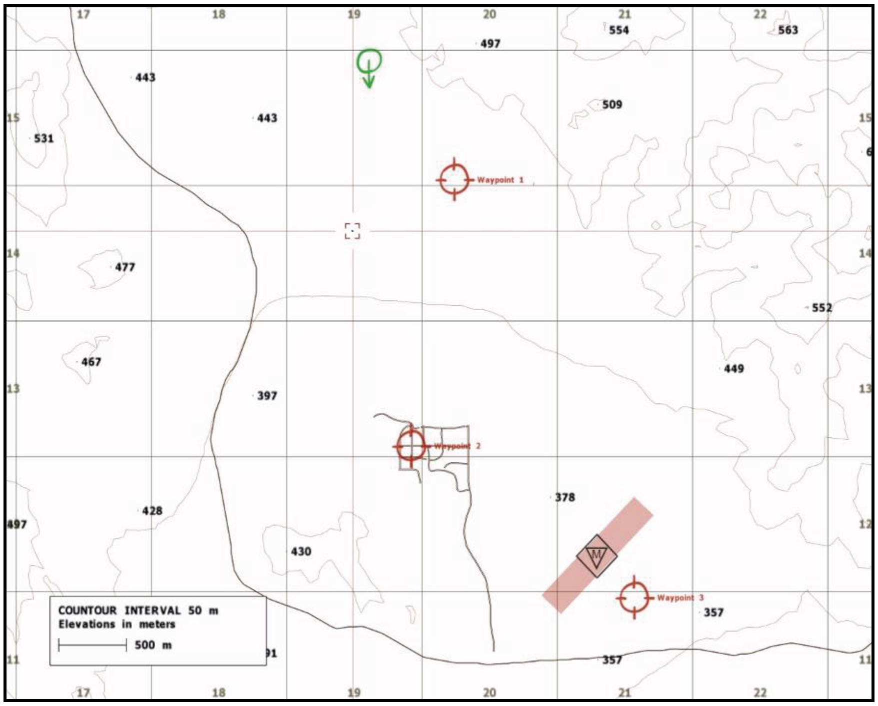

Figure A-3. Map C.

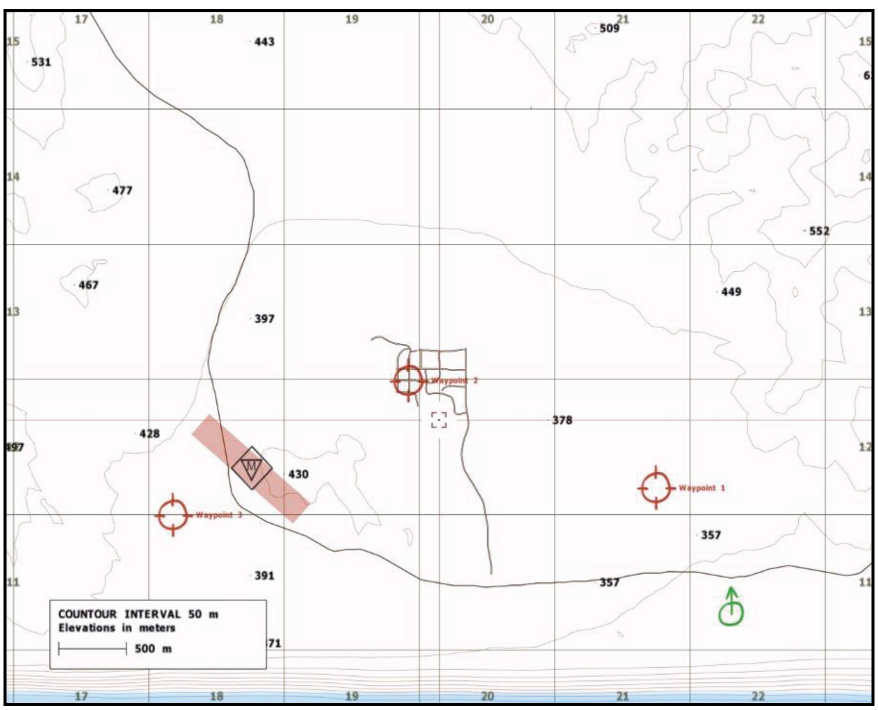

Figure A-4. Map D.

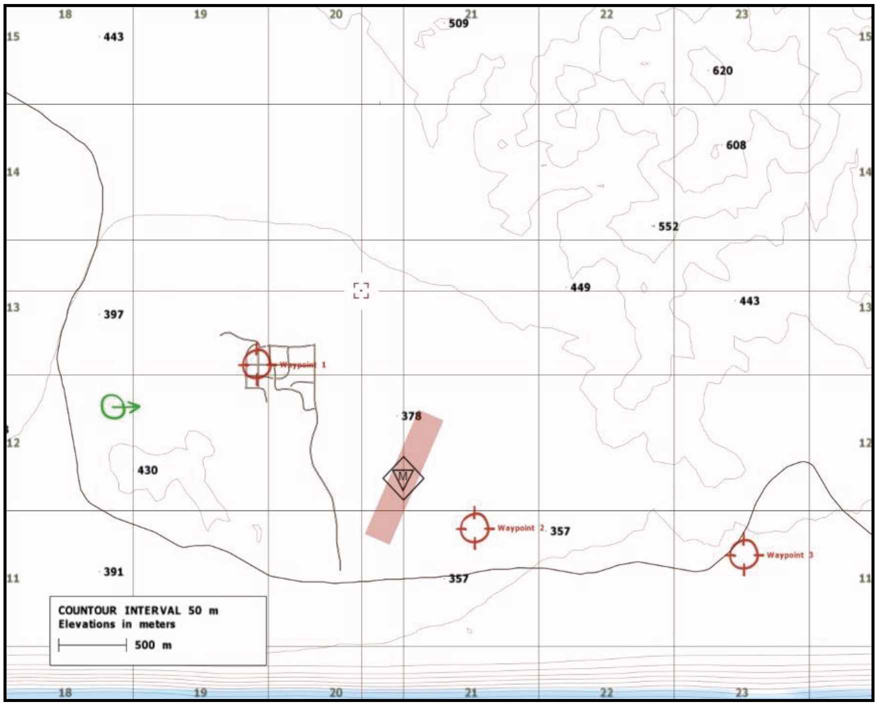

Figure A-5. Map E.

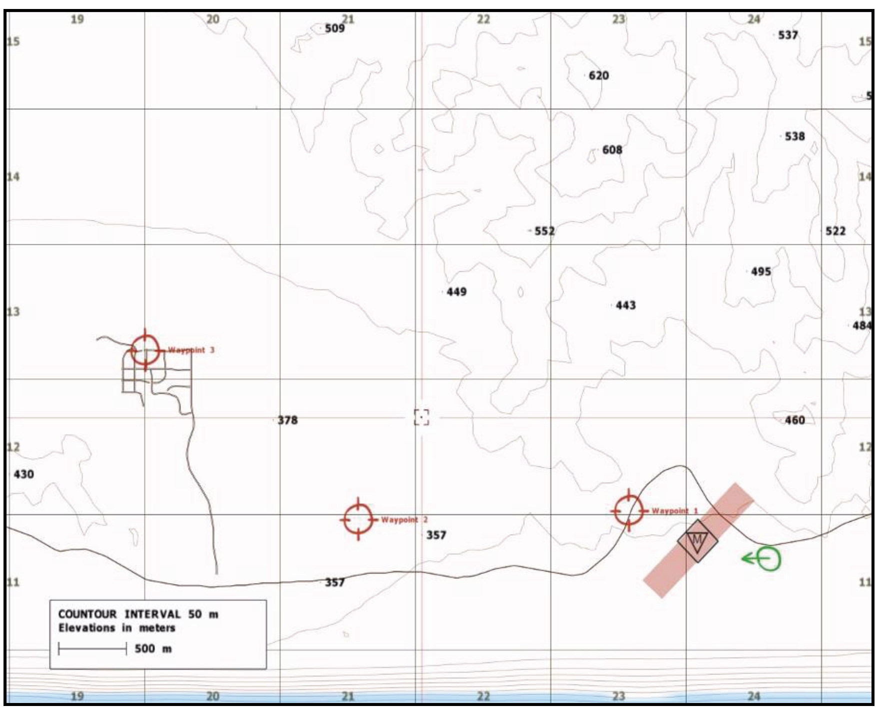

Figure A-6. Map F.

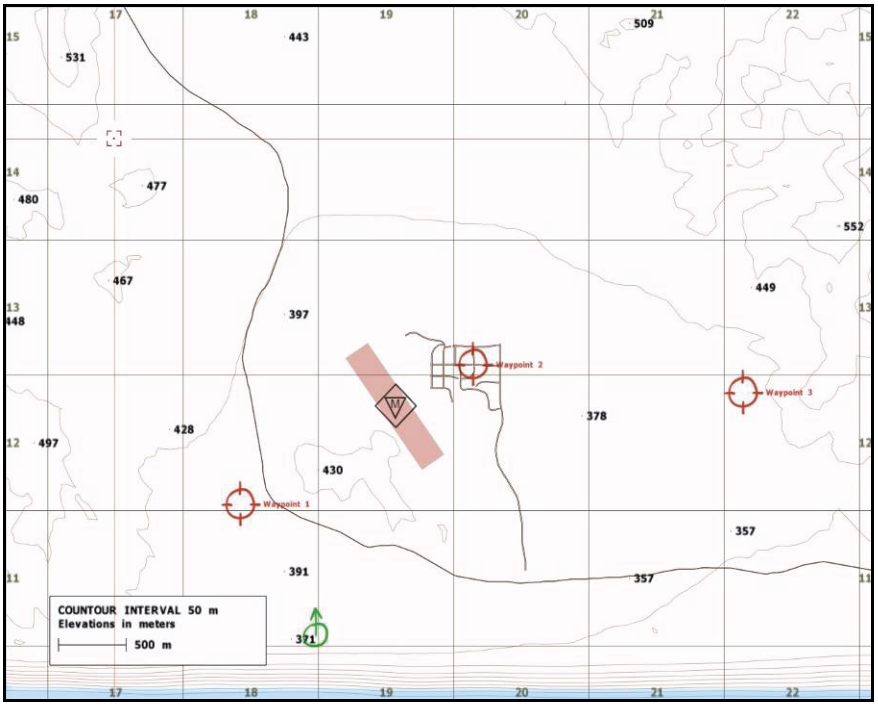

Figure A-7. Map G.

Appendix B. Questionnaires

Situational Awareness Rating Technique (SART)

Please enter your participant ID:

Please enter the mission ID:

Instructions: Please answer these questions with regard to the preceding scenario.

Instability of Situation:
How changeable is the situation? Is the situation highly unstable and likely to change suddenly (high), or is it very stable and straight forward (low)?

○ Low ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ High

Complexity of Situation:
How complicated is the situation? Is it complex with many interrelated components (high) or is it simple and straightforward (low)?

○ Low ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ High

Variability of Situation:
How many variables are changing in the situation? Are there are large number of factors varying (high) or are there very few variables changing (low)?

○ Low ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ High

Arousal:
How aroused are you in the situation? Are you alert and ready for activity (high) or do you have a low degree of alertness (low)?

○ Low ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ High

Concentration of Attention:
How much are you concentrating on the situation? Are you bringing all your thoughts to bear (high) or is your attention elsewhere (low)?

○ Low ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ High

Division of Attention:
How much is your attention divided in the situation? Are you concentrating on many aspects of the situation (high) or focussed on only one (low)?

○ Low ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ High

Spare Mental Capacity:
How much mental capacity do you have to spare in the situation? Do you have sufficient capacity to attend to many variables (high) or nothing to spare at all (low)?

○ Low ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ High

Information Quantity:
How much information have you gained about the situation? Have you received and understood a great deal of knowledge (high) or very little (low)?

○ Low ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ High

Information Quality:
How good is the information you have gained about the situation? Is the knowledge communicated very useful (high) or is it a new situation (low)?

○ Low ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ High

Familiarity with Situation:
How familiar are you with the situation? Do you have a great deal of relevant experience (high) or is it a new situation (low)?

○ Low ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ High

Submit

NASA - Task Load Index (TLX)

Please enter your participant ID:

Please enter the mission ID:

Instructions for Part 1: Please answer these questions with regard to the preceding scenario.

Mental Demand:
How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)?

○ Low ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ High

Temporal Demand:
How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred?

○ Low ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ High

Performance:
How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

○ Good ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ Poor

Effort:
How hard did you have to work (mentally and physically) to accomplish your level of performance?

○ Low ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ High

Frustration:
How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

○ Low ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ High

Instructions for Part 2: From the following pairs, select the scale title that represents the more important contributor to workload for the task you performed in the preceeding scenario.

○ Temporal Demand
○ Mental Demand

○ Mental Demand
○ Performance

○ Temporal Demand
○ Effort

○ Frustration
○ Mental Demand

○ Effort
○ Performance

○ Performance
○ Frustration

○ Frustration
○ Effort

○ Temporal Demand
○ Frustration

○ Performance
○ Temporal Demand

○ Mental Demand
○ Effort

Submit

Modality Evaluation

Please enter your participant ID:

Please enter the mission ID:

Instructions: Please answer these questions with regard to the preceding scenario:

Navigation was effective.
- Strongly Agree
- Agree
- Neutral
- Disagree
- Strongly Disagree

Navigation was efficient.
- Strongly Agree
- Agree
- Neutral
- Disagree
- Strongly Disagree

Navigation was simple.
- Strongly Agree
- Agree
- Neutral
- Disagree
- Strongly Disagree

The alert was easily noticed.
- Strongly Agree
- Agree
- Neutral
- Disagree
- Strongly Disagree

The alert was effective at getting my attention.
- Strongly Agree
- Agree
- Neutral
- Disagree
- Strongly Disagree

The alert was helpful.
- Strongly Agree
- Agree
- Neutral
- Disagree
- Strongly Disagree

The alert was annoying or unnecesary.
- Strongly Agree
- Agree
- Neutral
- Disagree
- Strongly Disagree

Submit

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Appendix C. SART Subscale Score Mean Differences (ANOVA *post hoc* analyses) (Experiment 1)

Table C-1. Mean differences between modalities in SART demand subscale score.

Modality	Head-Up Icon	Moving Map	Monaural Speech	Spatial Speech	Spatial Tone
Baseline	3.000 (p = .080)	**2.643 (p = .018)**	0.000	-0.500 (p = .837)	-4.857 (p = .067)
Head-Up Icon		-0.357 (p = .705)	-3.000 (p = .071)	-3.500 (p = .080)	**-7.857 (p = .006)**
Moving Map			**-2.643 (p = .032)**	-3.143 (p = .122)	**-7.500 (p = .005)**
Monaural Speech				-0.500 (p = .786)	**-4.857 (p = .014)**
Spatial Speech					**-4.357 (p = .015)**

Bold blocks indicate significant differences.

Table C-2. Mean differences between modalities in SART demand subscale score.

Modality	Head-Up Icon	Moving Map	Monaural Speech	Spatial Speech	Spatial Tone
Baseline	-0.714 (p = .547)	-2.643 (p = .108)	0.643 (p = .611)	2.357 (p = .070)	**5.643 (p = .006)**
Head-Up Icon		-1.929 (p = .111)	1.357 (p = .260)	**3.071 (p = .031)**	**6.357 (p = .008)**
Moving Map			**3.286 (p = .032)**	**5.000 (p = .014)**	**8.286 (p = .004)**
Monaural Speech				1.714 (p = .258)	**5.000 (p = .026)**
Spatial Speech					**3.286 (p = .018)**

Bold blocks indicate significant differences.

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Appendix D. NASA-TLX Subscale Score Mean Differences (ANOVA *post hoc* analyses) (Experiment 1)

Table D-1. Mean differences between modalities in NASA-TLX mental demand subscale score.

Modality	Head-Up Icon	Moving Map	Monaural Speech	Spatial Speech	Spatial Tone
Baseline	**14.500 (*p* = .002)**	**12.071 (*p* = .001)**	**13.214 (*p* = .001)**	**12.214 (*p* = .014)**	2.214 (*p* = .584)
Head-Up Icon		-2.429 (*p* = .266)	-1.286 (*p* = .481)	-2.286 (*p* = .434)	**-12.286 (*p* = .006)**
Moving Map			1.143 (*p* = .640)	0.143 (*p* = .965)	**-9.857 (*p* = .008)**
Monaural Speech				-1.000 (*p* = .668)	**-11.000 (*p* = .003)**
Spatial Speech					**-10.000 (*p* = .005)**

Bold blocks indicate significant differences.

Table D-2. Mean differences between modalities in NASA-TLX temporal demand subscale score.

Modality	Head-Up Icon	Moving Map	Monaural Speech	Spatial Speech	Spatial Tone
Baseline	**3.786 (*p* = .007)**	**3.357 (*p* = .004)**	0.857 (*p* = .500)	-0.357 (*p* = .808)	0.643 (*p* = .501)
Head-Up Icon		-0.429 (*p* = .396)	**-2.929 (*p* = .016)**	**-4.143 (*p* = .029)**	**-3.143 (*p* = .035)**
Moving Map			**-2.500 (*p* = .019)**	**-3.714 (*p* = .026)**	**-2.714 (*p* = .026)**
Monaural Speech				-1.214 (*p* = .366)	-0.214 (*p* = .859)
Spatial Speech					1.000 (*p* = .488)

Bold blocks indicate significant differences.

Table D-3. Mean differences between modalities in NASA-TLX effort subscale score.

Modality	Head-Up Icon	Moving Map	Monaural Speech	Spatial Speech	Spatial Tone
Baseline	**9.143 (*p* = .004)**	**8.643 (*p* = .007)**	4.143 (*p* = .103)	**6.286 (*p* = .040)**	1.000 (*p* = .692)
Head-Up Icon		-0.500 (*p* = .646)	**-5.000 (*p* = .032)**	-2.857 (*p* = .069)	**-8.143 (*p* = .006)**
Moving Map			**-4.500 (*p* = .044)**	-2.357 (*p* = .187)	**-7.643 (*p* = .008)**
Monaural Speech				2.143 (*p* = .228)	-3.143 (*p* = .147)
Spatial Speech					**-5.286 (*p* = .021)**

Bold blocks indicate significant differences.

Table D-4. Mean differences between modalities in NASA-TLX frustration subscale score.

Modality	**Head- Up Icon**	**Moving Map**	**Monaural Speech**	**Spatial Speech**	**Spatial Tone**
Baseline	0.071 (*p* = .885)	0.143 (*p* = .752)	-1.500 (*p* = .363)	-1.714 (*p* = .357)	**-16.143 (*p* = .002)**
Head-Up Icon		0.071 (*p* = .336)	-1.571 (*p* = .335)	-1.786 (*p* = .332)	**-16.214 (*p* = .002)**
Moving Map			-1.643 (*p* = .308)	-1.857 (*p* = .310)	**-16.286 (*p* = .002)**
Monaural Speech				-0.214 (*p* = .931)	**-14.643 (*p* = .005)**
Spatial Speech					**-14.429 (*p* = .002)**

Bold blocks indicate significant differences.

Appendix E. Scenario Maps (Experiment 2)

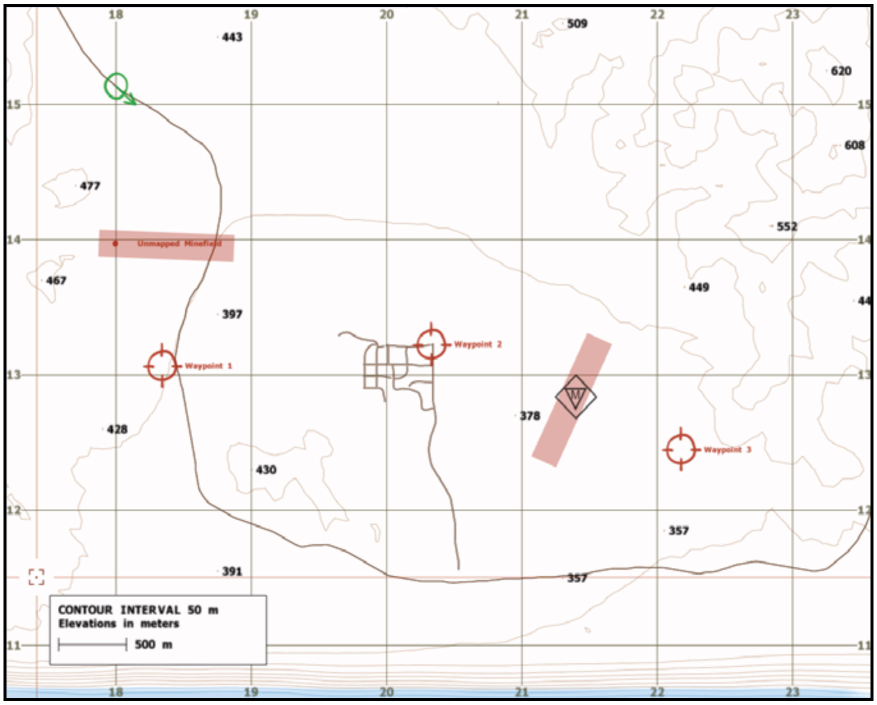

Figure E-1. Map A.

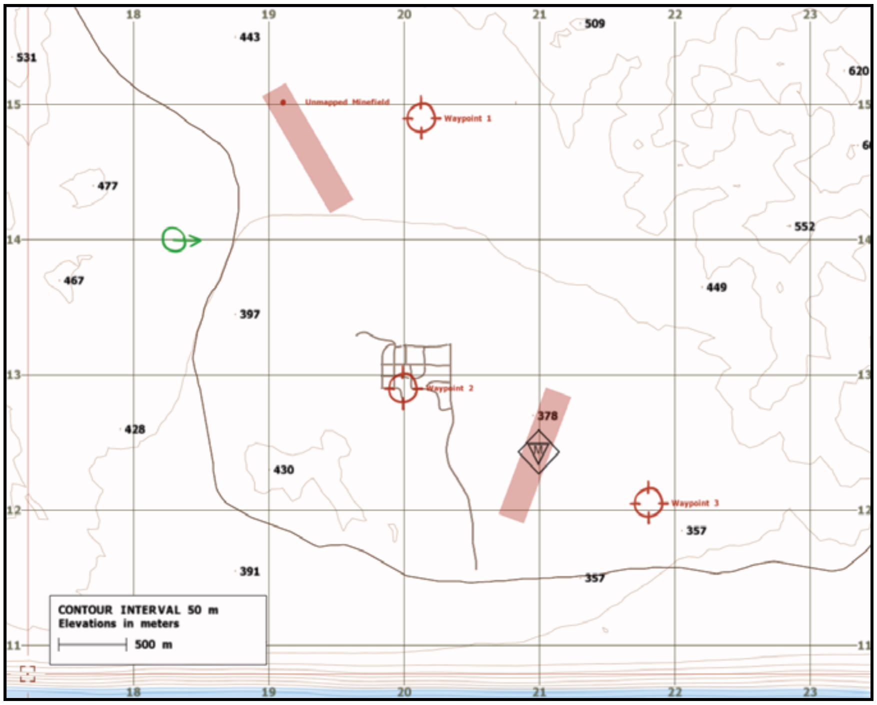

Figure E-2. Map B.

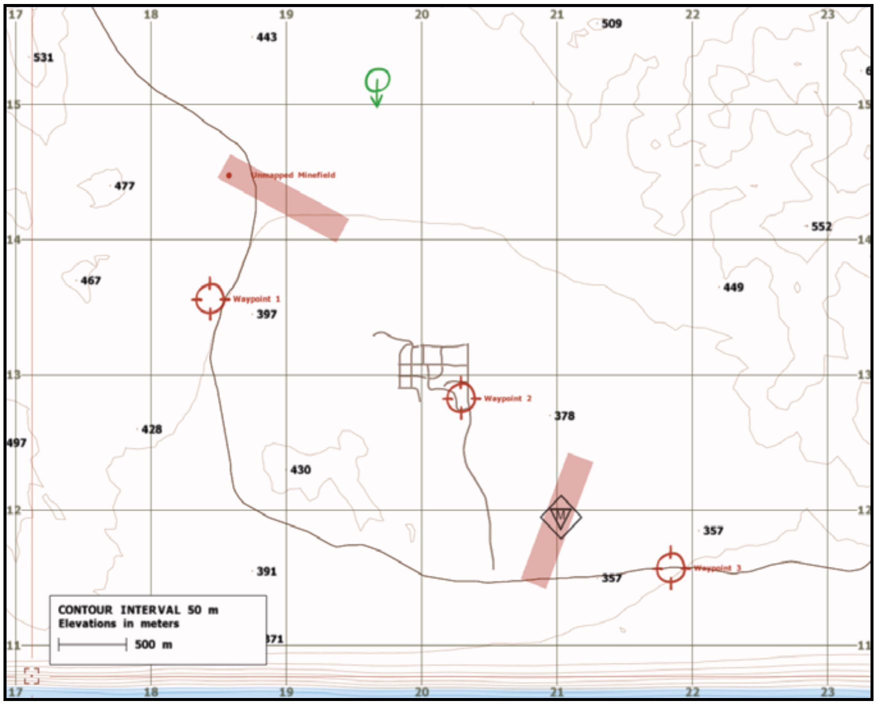

Figure E-3. Map C.

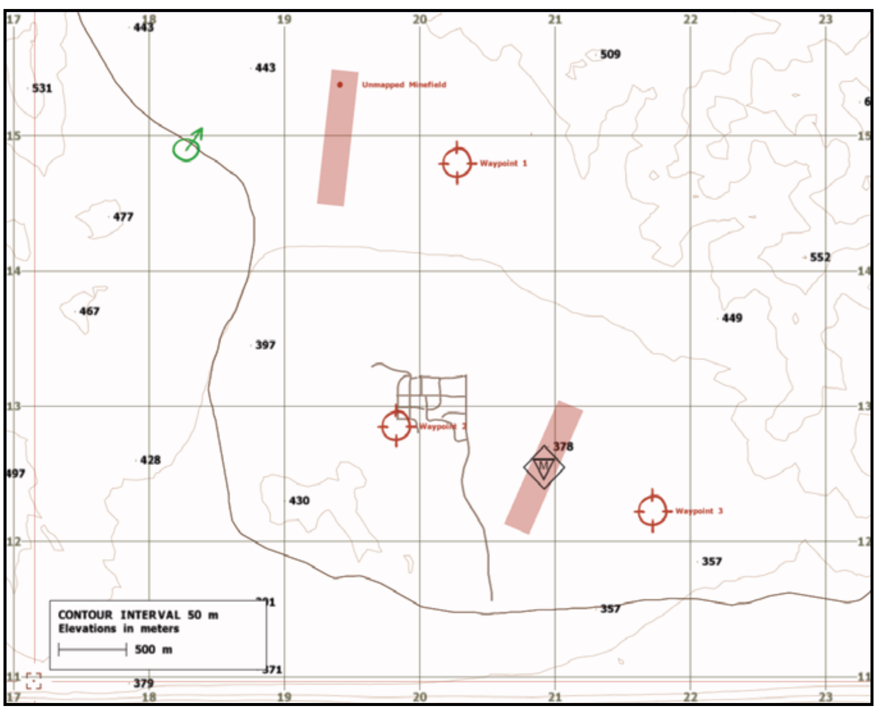

Figure E-4. Map D.

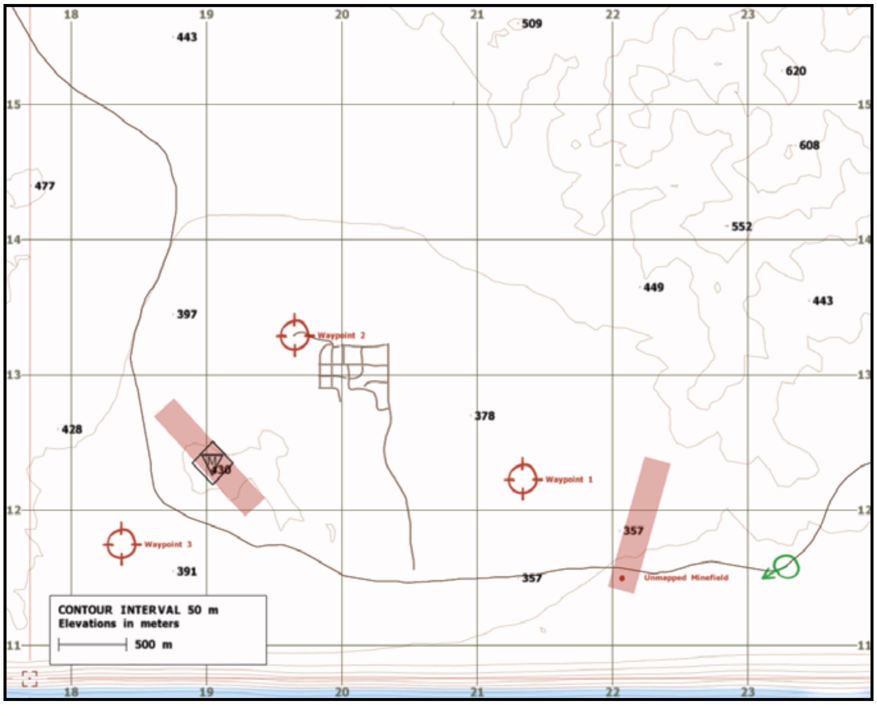

Figure E-5. Map E.

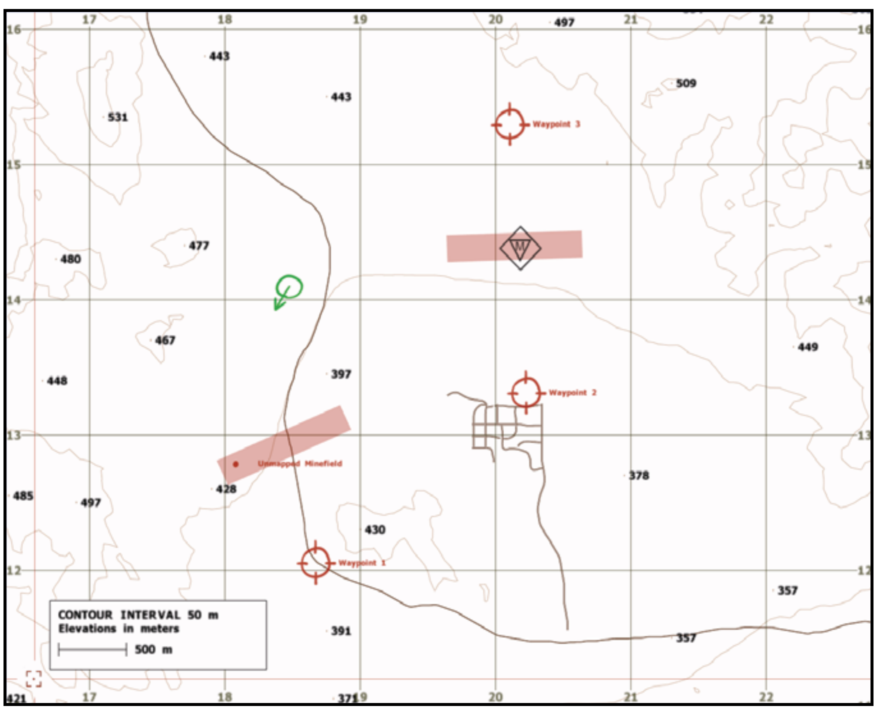

Figure E-6. Map F.

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Appendix F. SART Subscale Score Mean Differences (ANOVA *post hoc* analyses) (Experiment 2)

Table F-1. Mean differences between modalities in SART demand subscale score.

Modality	Head-Up Icon	Moving Map	Monaural Speech	Spatial Speech	Tactile
Baseline	**7.167 ($p < .001$)**	**6.667 ($p = .001$)**	**4.833 ($p = .003$)**	**5.722 ($p < .001$)**	3.389 ($p = .059$)
Head-Up Icon		-0.500 ($p = .719$)	-2.333 ($p = .191$)	-1.444 ($p = .398$)	**-3.778 ($p = .013$)**
Moving Map			-1.833 ($p = .367$)	-0.944 ($p = .602$)	-3.278 ($p = .082$)
Monaural Speech				-0.889 ($p = .419$)	-1.444 ($p = .296$)
Spatial Speech					-2.333 ($p = .199$)

Bold blocks indicate significant differences.

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Appendix G. NASA-TLX Subscale Score Mean Differences (ANOVA *post hoc* analyses) (Experiment 2)

Table G-1. Mean differences between modalities in NASA-TLX mental demand subscale score.

Modality	Head-Up Icon	Moving Map	Monaural Speech	Spatial Speech	Tactile
Baseline	**20.444 (p < .001)**	**17.056 (p < .001)**	**14.333 (p < .001)**	**12.222 (p = .001)**	**15.389 (p < .001)**
Head-Up Icon		-3.389 (p = .161)	**-6.111 (p = .004)**	**-8.222 (p = .009)**	**-5.056 (p = .019)**
Moving Map			-2.722 (p = .264)	-4.833 (p = .118)	-1.667 (p = .457)
Monaural Speech				-2.111 (p = .287)	1.056 (p = .601)
Spatial Speech					3.167 (p = .210)

Bold blocks indicate significant differences.

Table G-2. Mean differences between modalities in NASA-TLX effort subscale score.

Modality	Head-Up Icon	Moving Map	Monaural Speech	Spatial Speech	Tactile
Baseline	**7.611 (p = .008)**	5.444 (p = .065)	**4.667 (p = .034)**	**5.667 (p = .025)**	4.611 (p = .106)
Head-Up Icon		**-2.167 (p = .030)**	-2.944 (p = .181)	-1.944 (p = .358)	-3.000 (p = .104)
Moving Map			-0.778 (p = .712)	0.222 (p = .913)	-0.833 (p = .654)
Monaural Speech				1.000 (p = .627)	-0.056 p = .978)
Spatial Speech					-1.056 (p = .595)

Bold blocks indicate significant differences.

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